Report

Task 4: Problem and Solution Identification and Prioritization for Taylor Run, Alexandria, Virginia

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CH2MHILL®

Executive Summary

The City of Alexandria, Virginia (the City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented in phases by watershed. The watersheds include Hooffs Run, Four Mile Run, Holmes Run, Cameron Run, Taylor Run, Strawberry Run, Potomac River, and Backlick Run.

This report focuses on problem and solution identification (Task 4) for capacity issues in the Taylor Run watershed. It summarizes the problem identification steps, solution development, solution scoring, and alternatives analysis. This task has resulted in three watershed-wide alternatives aimed at resolving capacity-related problems in Taylor Run. Additionally, this task has provided the City with a decision making process for evaluating the benefits of potential stormwater management (SWM) projects.

In Taylor Run, the existing intensity-duration-frequency (IDF) design hyetograph for the 10-year return period, based on peak intensity, was used to simulate rainfall runoff and stormwater flow within the watershed.

The objectives of this phase of the study were to 1) identify and prioritize capacity problems based on modeling results from Task 2 of this project, and 2) develop and prioritize solutions to address those problems. The first objective was accomplished in two steps. The first step included evaluating each stormwater junction in the drainage network using a scoring system to identify problems based on several criteria, including the severity of flooding, proximity to critical infrastructure and roadways, identification of problems by city staff and the public, and opportunity for overland relief. In the next step of this objective, high-scoring junctions (that is, higher-priority problems) were grouped together to form high-priority problem areas. In total, 12 high-priority problem areas were identified in the Taylor Run watershed. Flooding locations falling outside of the high-priority problem areas were either flooding at isolated structures, or did not score high on the scoring criteria. These flooding problems were not addressed by solutions in this project.

The second objective involved developing and prioritizing solutions to address capacity limitations within the 12 high-priority problem areas. To accomplish this objective, several strategies involving different technologies were examined, including improving conveyance by increasing hydraulic capacity, reducing capacity limitations by adding distributed storage to the system, and reducing stormwater inflows by implementing green infrastructure (GI). Each of these strategies required a different modeling approach. Conveyance improvements were modeled by increasing pipe diameter in key locations within the problem area, storage was added as storage nodes based on a preliminary siting exercise, and GI was modeled as a reduction in impervious area at three different implementation levels: high, medium, and low. A single model run was set up and run for each strategy addressing all 12 high-priority problem areas and the results were compiled for the alternatives and prioritization evaluation. Solutions were evaluated based on several criteria, including drainage improvement/flood reduction, environmental compliance, sustainability and social benefits, asset management and maintenance implications, constructability, and public acceptance. Planning-level capital costs were developed for each solution to facilitate a benefit cost analysis and prioritization process.

The results of the solution identification and prioritization analysis show the following results for Taylor Run:

- In terms of solution technology performance:
  - Conveyance solutions generally have the greatest overall benefit.
  - Conveyance and storage solutions generally provide the greatest flood reduction of the technologies/approaches analyzed.
- In terms of costs:
  - A low level of GI implementation generally has the greatest benefit/cost score, but did not usually meet the minimum threshold for flood reduction.

- Conveyance projects generally provide the most economical stormwater volume reduction in terms of dollars per gallon of flood reduction within a high-priority problem area.

Three watershed-wide alternatives were developed, including:

- Alternative 1: Most cost-effective solution for each problem area (lowest dollar-per-gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to address the worst problem areas to the extent practicable

Conveyance projects dominate the list of solutions for all three watershed-wide alternatives in Taylor Run. This is because the Taylor Run storm sewer system is made up of smaller systems that discharge into the Taylor Run stream, which runs from north to south. Many of the capacity issues affect a few pipes at the downstream end of these smaller systems near the outlet to the stream, and do not occur far upstream. As such, conveyance improvements increase capacity, eliminating flooding in these localized areas, and because there are no downstream collection systems, there are no adverse effects. Because impacts to the stream channel are not being explicitly evaluated, if a project increases the peak flow to the stream channel this is not accounted for.

A summary of the results is provided in Table ES-1.

TABLE ES-1
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Alternative 1 - Best Cost Efficiency	Alternative 2 - Best Benefit/Cost Ratio	Alternative 3 – Highest-priority Problems
Total Cost ($ Millions)	$4.87	$4.89	$7.36
Total Benefit Score	501	516	538
Overall Benefit/Cost	103	106	73
Total Flood Reduction (MG)	4.47	4.43	4.66
$/Gallon of Flood Reduction	$1.10	$1.10	$1.58

Because of the dominance of conveyance projects, Alternative 1 and Alternative 2 only differ in one of the 12 problem areas. Problem Area 210 where storage is the highest ranked solution for cost efficiency and conveyance is the highest ranked solution for benefit cost. Alternative 1 and Alternative 2 provide similar amounts of flood reduction for essentially the same total cost and cost per gallon of flood reduction but Alternative 2 provides a marginally higher benefit and benefit/cost scores. Alternative 3 provides the highest total volume of flood reduction, but it also has the highest cost per gallon of flood reduction and lowest benefit and benefit/cost scores. Therefore, Alternative 2 is the most beneficial and cost effective watershed-wide alternative. Model results for the existing conditions model and the Alternative 2 watershed-wide alternative are presented in Figures ES-1 and ES-2.

FIGURE ES-1
Existing Conditions Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

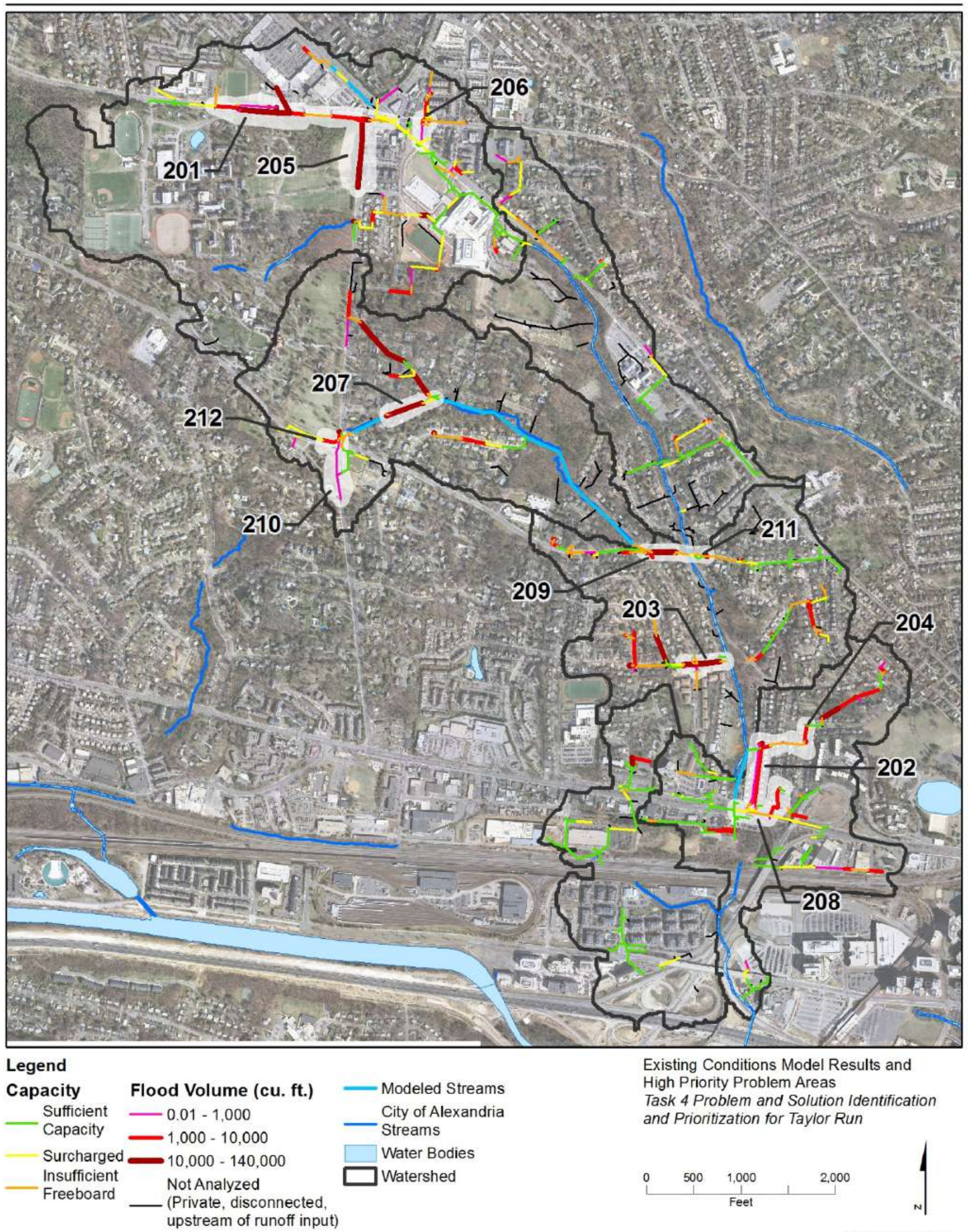
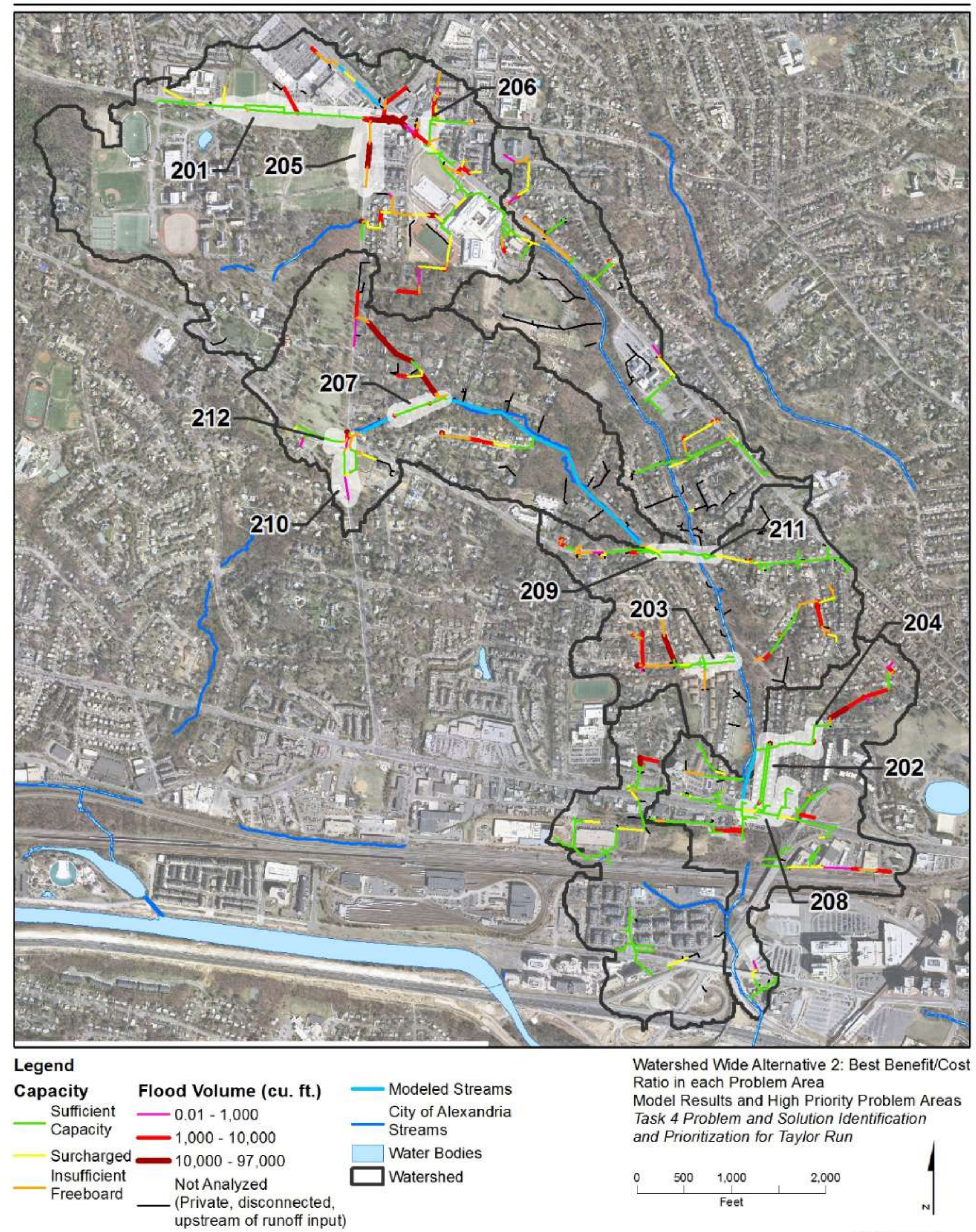


FIGURE ES-2
Alternative 2: Best Benefit/Cost Ratios Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

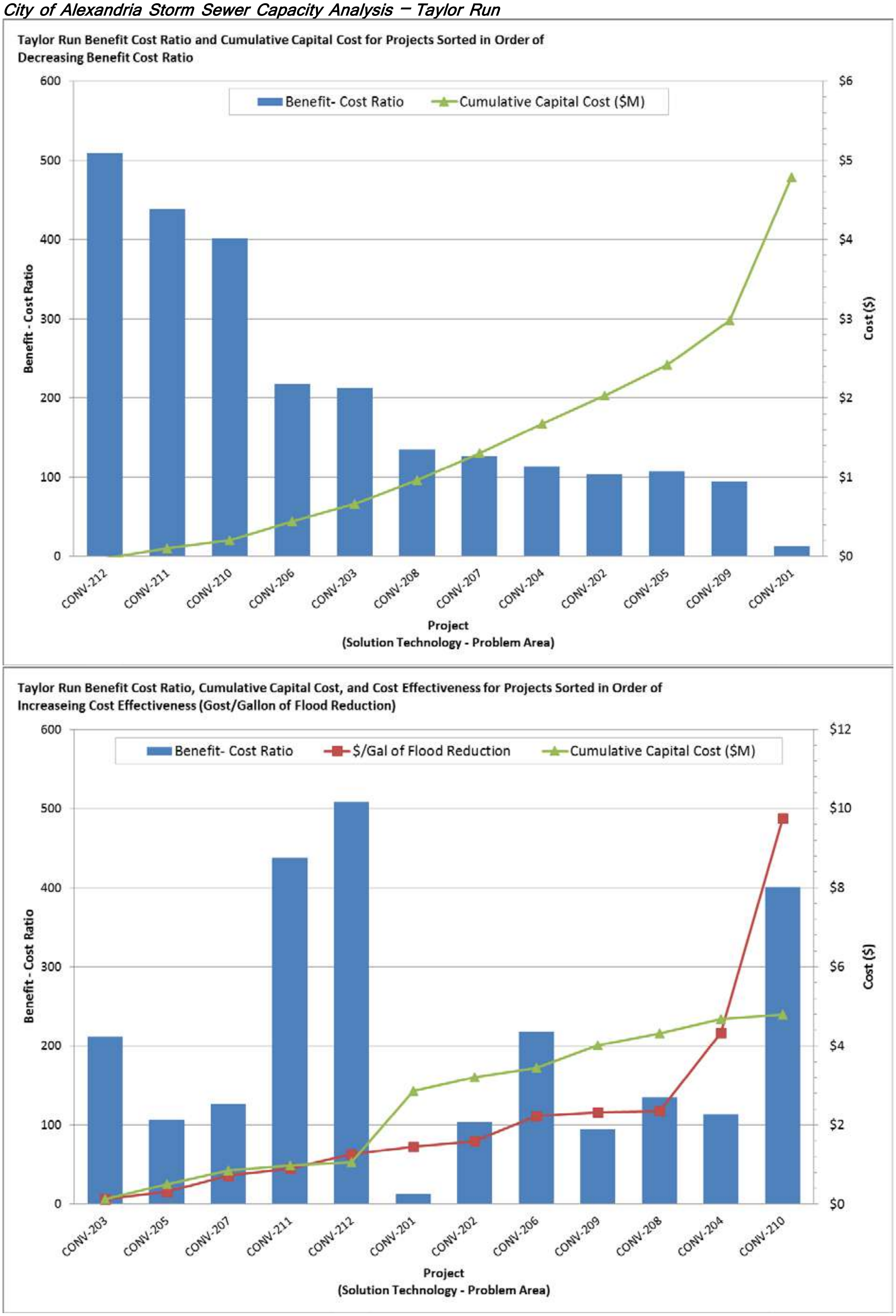


When developing a capital improvement plan, the benefit cost or cost efficiency ($/gallon of flood reduction) are typically used to guide the order in which projects are implemented. Prioritization results for Alternative 2 are presented in Figure ES-3. The top chart shows the total benefit score and the cumulative capital cost of the alternative. The solutions are provided in order of decreasing benefit cost ratio; solutions with the greatest benefit cost are presented on the left and solutions with the lowest benefit cost are presented on the right. The bottom chart shows the benefit/cost ratio for each solution in the watershed-wide alternative in order of increasing cost/gallon of flood reduction. Both charts show the cumulative capital cost plotted on the secondary axis. The solutions on both charts are named by the technology: conveyance (CONV), storage (STOR), low green infrastructure (LGI), medium GI (MGI), or high GI (HGI), and the problem area number.

It should be noted that the model does not include analysis on private property, but applies assumed runoff loads as inputs to the public conveyance system. The City chose not to include existing private or public stormwater management facilities upstream of the modeled collection system because of the limited available information on these facilities and a concern that the facilities may not be performing as designed. When the City moves forward into detailed evaluation and design of selected projects, it will be important to fully evaluate and account for the benefits of any existing stormwater management facilities.

The hydraulic modeling results and costs presented in this report should be reviewed with the understanding that several assumptions were made to fill data gaps in the hydraulic model, and proposed solutions and costs were developed on a planning level.

FIGURE ES-3
Alternative 2: Best Benefit/Cost Ratio Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



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Acronyms and Abbreviations

bgs	below ground surface
cfs	cubic feet per second
City	City of Alexandria, Virginia
ft^2	square feet
ft^3	cubic feet
GI	green infrastructure
HGI	high green infrastructure
HGL	hydraulic grade line
hrs	hours
ID	identification
IDF	intensity-duration-frequency
LF	linear feet
LGI	low green infrastructure
MG	million gallons
MGI	medium green infrastructure
ROW	right-of-way
SWM	stormwater management
TM	technical memorandum

SECTION 1

Introduction

The City of Alexandria, Virginia (the City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented on a watershed basis, with Taylor Run being the subject of this report. City of Alexandria watersheds are shown on Figure 1-1.

1.1 Background

The project consists of four major subtasks related to the model development and modeling. These four tasks and related technical memorandums (TMs) are described below.

- Task 1 – Review and propose revisions to the City's stormwater design criteria.
  - *Updated Precipitation Frequency Results and Synthesis of New IDF Curves for the City of Alexandria, Virginia* (CH2M HILL, 2009a)
  - *Sea Level Rise Potential for the City of Alexandria, Virginia* (CH2M HILL, 2009b)
  - *Rainfall Frequency and Global Change Model Options for the City of Alexandria* (CH2M HILL, 2011)
- Task 2 – Analyze the City's stormwater collection system capacity.
  - *Inlet Capacity Analysis for City of Alexandria Storm Sewer Capacity Analysis* (CH2M HILL, 2012)
  - *Stormwater Capacity Analysis for Taylor Run Watershed, City of Alexandria, Virginia* (CH2M HILL, 2016a)
- Task 3 – Survey collection system facilities on pipes 24 inches and larger, to fill data gaps.[1]
  - *City of Alexandria Storm Sewer Capacity Analysis (CASSCA) Taylor Run Sewershed Condition Assessment* (Baker, 2013)
- Task 4 – Identify problem areas and suggest solutions.
  - *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014)

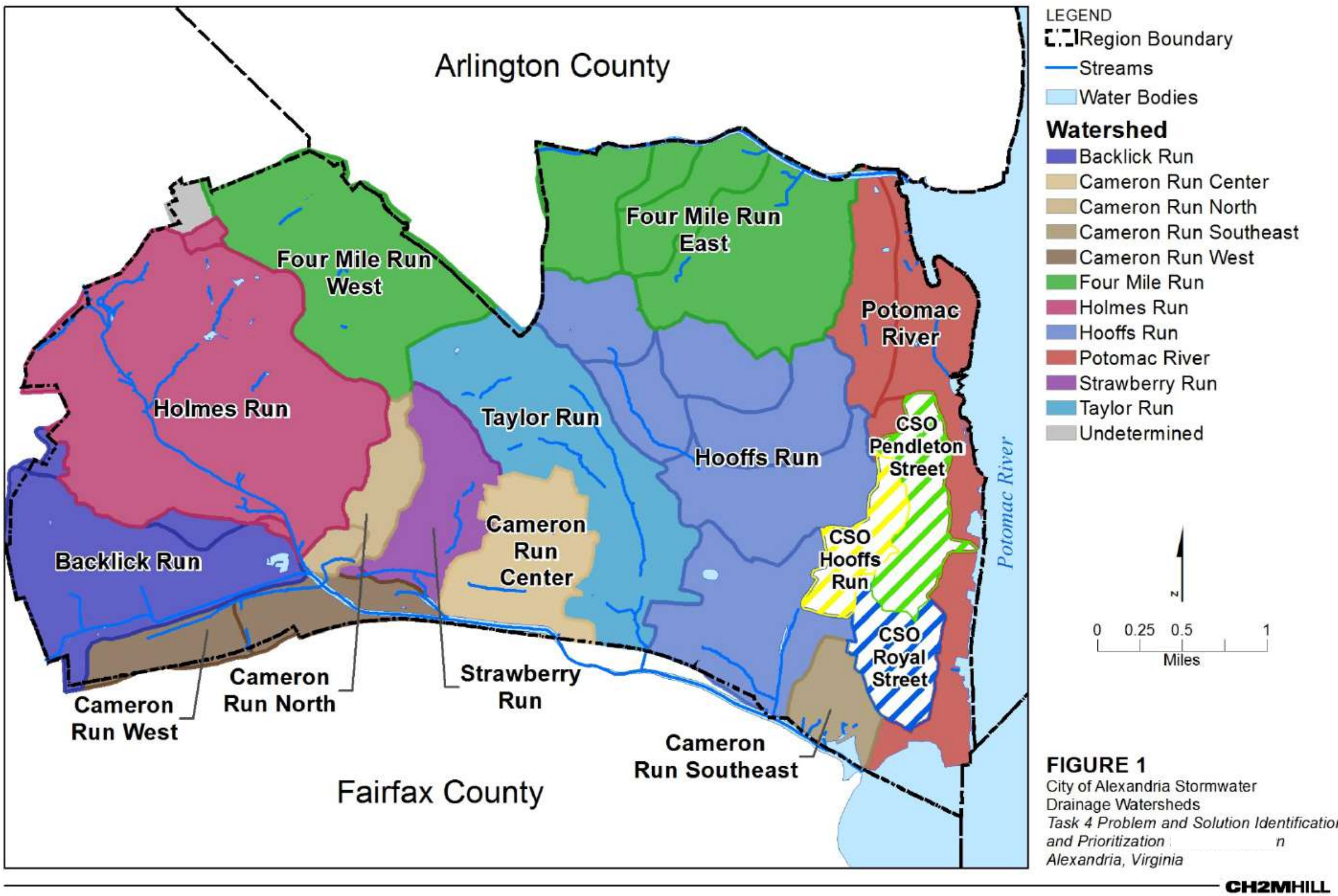
1.2 Objectives

Tasks 1 through 3 focused on model development and capacity analysis of the existing system. The purpose of Task 4 is to identify and prioritize problems modeled during the Task 2 capacity analysis and to suggest and prioritize conveyance, storage, and green infrastructure (GI) solutions to resolve the identified capacity limitations.

This report describes the methodology and results of Task 4 for the stormwater collection system in the Taylor Run watershed. Figure 1-1 shows the City's stormwater drainage watersheds.

[1] Although originally intended to improve data quality where the model predicted capacity limitations, the scope of Task 3 was expanded, and field surveys were completed prior to Task 2 to fill data gaps and to improve the model development process.

FIGURE 1-1
Stormwater Drainage Watersheds, City of Alexandria, Virginia
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



SECTION 2

Approach

The approach to identifying and prioritizing problems and solutions included several distinct steps: identifying and prioritizing problems, developing and modeling solutions, prioritizing solutions and, finally, developing watershed-wide scenarios. This approach, described in this section, is broken into two major components: prioritization, and modeling.

2.1 Prioritization

The focus of Task 4 is to prioritize problem areas based on Task 2 modeling results, develop solutions to resolve the problem areas, then prioritize those solutions. Prior to beginning the Task 4 analysis, City of Alexandria staff and consultants from CH2M HILL and Michael Baker convened in a workshop on November 14, 2012 to discuss the objectives, approach, and desired outcomes of this phase of the project. The major objectives of the workshop were to define the prioritization process, identify the key evaluation criteria for scoring and ranking problems and solutions, and define relative criteria weights. The prioritization process, described below, is similar for both problems and solutions, and includes several distinct steps.

- **Define evaluation criteria**: Evaluation criteria for problems and solutions were defined during the Task 4 workshop with input from City staff from the Engineering & Design, Office of Environmental Quality, and Maintenance Divisions of Transportation and Engineering Services. These criteria, which are summarized in this report, were used to assess the severity of problems and the benefit of solutions.
- **Weight evaluation criteria**: Each evaluation criterion was assigned a weight (0 to 100) by Task 4 workshop participants. The weights quantify the relative importance of each evaluation criteria and build a defensible foundation for problem and solution ranking.
- **Define scoring system**: A scoring system was developed for each evaluation criteria. This provided a method for ranking problems and solutions within evaluation criteria. Scoring systems for problem area and solution evaluation criteria are defined in this report.
- **Score and rank alternatives**: Problems and solutions were scored and ranked using the evaluation criteria scoring systems, which are described in the TM entitled *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014) and include:
    - *Score and Rank Problems:* A score of 0 through 10 was assigned to stormwater junctions in the modeled system for each evaluation criteria. Weights were then applied to the score calculated for each evaluation criteria to come up with an overall weighted score for each junction. The overall score was used to rank problems; then, high-priority problem areas were identified as groupings of hydraulically connected junctions and pipes. Solutions were investigated for the highest-priority problem areas.
    - *Score and Rank Solutions*: Solutions were developed for high-priority problem areas identified in the previous step. A score of 0 through 10 was assigned to solutions for each evaluation criteria. Then the weights were applied to the score calculated for each evaluation criteria to calculate an overall weighted benefit score. Solutions were ranked based on the overall score as well as the benefit/cost score, which is the overall benefit score divided by the capital cost of the solution. The solution evaluation is presented at the end of this report.
- **Perform "what-if" analysis to refine process**: After completing the prioritization, the process was examined to be sure the results met the expectations of the City. The result of this step was the inclusion of a 22 percent minimum threshold for flood reduction (any project that produced less than 22 percent reduction in volume of flooding was eliminated) to help focus the solution identification process. This threshold was selected by City staff based on best engineering judgment.
- **Evaluate watershed-wide scenarios**: Once individual solutions were evaluated, the solutions were grouped into three alternative watershed-wide scenarios. The scenarios were scored by summing scores and costs of

individual projects for comparison. The purpose of taking this watershed-wide look at solution sets was to evaluate the solutions in a holistic, system-wide manner to evaluate the composite effects of implementing various solutions across the system and to support selection of a set of solutions that will provide the greatest benefit for the least cost.

2.1.1 Problem Area Evaluation

Taylor Run watershed has a drainage area of 1.36 square miles, which is drained by the Taylor Run stream and its two unnamed tributaries (Trib 1.13 and Trib .37 per 2007 United States Army Corps of Engineers [USACE] Cameron Run Watershed Study). The Taylor Run storm sewer system is made up of smaller systems that discharge along the Taylor Run stream from north to south. As such, the effects of capacity issues are localized and do not extend throughout the system; rather, they usually occur at the downstream end of these smaller systems where they discharge to Taylor Run.

The problem area evaluation focused on identifying flooding problems that are extreme and/or in proximity to critical facilities. Although model results were presented for pipes, not junctions, in the Stormwater Capacity Analysis (Task 2), flooding occurs at a junction and not along the length of the pipe; therefore, stormwater junctions in the hydraulic model, not pipe segments, were scored for each of the problem area evaluation criteria. Raw scores for each criterion ranged from 0 to 10: 0 indicating the junction is not a priority and/or the evaluation criteria is not applicable, and 10 indicating the junction is a high priority. The problem area evaluation criteria include:

- Urban drainage/flooding
- Identification of problems by the public
- Identification of problems by City staff
- Proximity to critical infrastructure
- Proximity to critical roadways
- Opportunity for overland relief

Detailed descriptions of the problem scoring systems used in this evaluation are provided in the TM entitled *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014). The weighted score was computed using the raw score and normalized percent weight. Evaluation criteria and weights developed and agreed upon during the Task 4 workshop are presented in Table 2-1.

TABLE 2-1
Problem Area Evaluation Criteria and Weights
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area Evaluation Criteria	Weight	Normalized % Weight
Urban Drainage/Flooding	90	23.1
Public ID of Problem	73	18.8
City Staff ID of Problem	75	19.3
Proximity to Critical Infrastructure	58	14.9
Proximity to Critical Roadways	38	9.8
Opportunity for Overland Relief	55	14.1
Total	**389**	**100**

Note:
ID = Identification

After computing the weighted score for each junction, high-priority problem areas were identified as hydraulically connected groupings of junctions and pipes for the junctions with scores over 30. Scoring was based on results from the Task 2 model of the 10-year, 24-hour storm generated using the existing intensity-duration-frequency (IDF). The results of the problem area evaluation are presented in Section 3 of this report, Problem Identification.

The goal of delineating high-priority problem areas was to identify groupings of stormwater pipes causing capacity limitations so that conveyance, storage, and GI solutions could be developed for the area. This task was accomplished by starting with the highest-ranked junction score, which indicated it was the worst problem based on the problem area identification evaluation criteria, and reviewing the surrounding drainage network and model results to identify the pipes and junctions related to that high problem score. A polygon surrounding all the pipes related to the capacity limitation was digitized in ArcMap and was assigned a unique identifier. After completing this process for the highest-ranked junction score, the network and model results for the next-highest score were examined, and a new problem area was digitized. If the next highest-score was captured in the first high-priority area, it was skipped. This process was repeated for junctions with a score above 30, or the top 15 percent of junctions with a score over 0. Flooding locations falling outside of the high-priority problem areas were either flooding at isolated structures, or did not score high on the scoring criteria. These flooding problems were not addressed by solutions in this project.

2.1.2 Solution Evaluation

Solutions were developed to resolve or improve capacity limitations in the highest-priority problem areas. Three different technologies were evaluated: conveyance, storage, and GI. Modeling results, described in detail in the following sections, were used in conjunction with additional data from the City (for example, geospatial data on roads and critical infrastructure, capital improvement plans, maintenance plans) to score solutions for each of the following solution evaluation criteria:

- Urban drainage/flooding
- Environmental compliance
- EcoCity goals/sustainability
- Social benefits
- Integrated asset management
- City-wide maintenance implications
- Constructability
- Public acceptability

Detailed descriptions of the solution scoring systems used in this evaluation are provided in the TM entitled *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014). The weighted score was computed using the raw score and normalized percent weight. Evaluation criteria and weights agreed upon during the Task 4 workshop are presented in Table 2-2.

TABLE 2-2
Solution Evaluation Criteria and Weights
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Solution Evaluation Criteria	Weight	Normalized % Weight
Urban Drainage/Flooding	95	17.1
Environmental Compliance	93	16.8
EcoCity Goals/Sustainability	50	9.0
Social Benefits	40	7.2
Integrated Asset Management	73	13.2
City-wide Maintenance Implications	90	16.2
Constructability	60	10.8
Public Acceptability	53	9.6
Total	**554**	**100**

2.2 Modeling

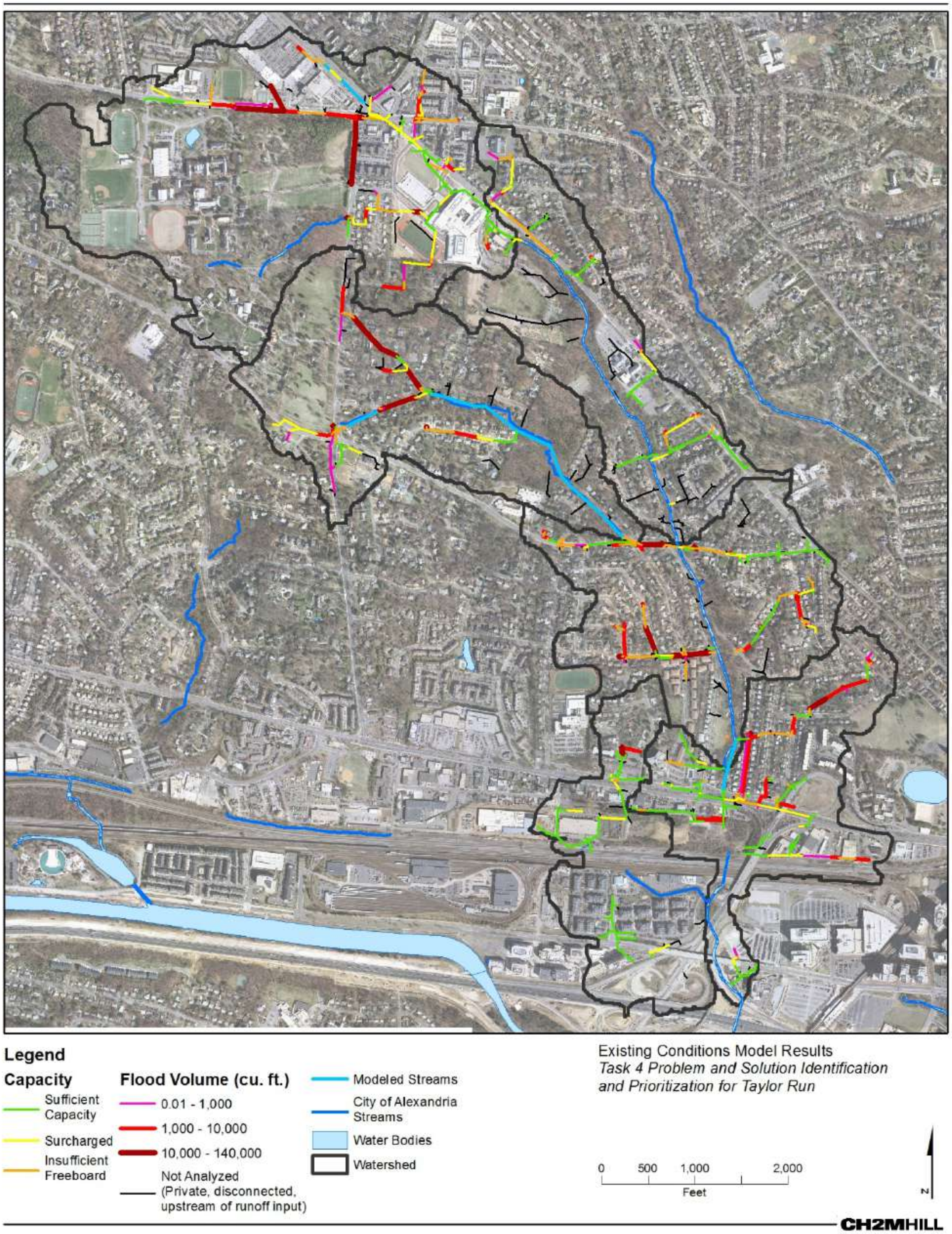
To support the Task 4 analysis, the Taylor Run watershed capacity was analyzed using commercially available and public domain computer models that are both widely used and industry-accepted. The details of the hydrologic and hydraulic modeling are documented in the Task 2 TM, *Stormwater Capacity Analysis for Taylor Run Watershed, City of Alexandria, Virginia* (CH2M HILL, 2016a). The existing conditions model of the 10-year, 24-hour design storm based on the City's existing IDF curve served as the basis for modeling in the Task 4 analysis. Figure 2-1 and Table 2-3 present the Task 2 results for reference.

TABLE 2-3
Summary of Task 2 Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Existing Conditions Results			
	Conduit Length (LF)	**Percent of Total Length (%)**	**Total Duration (hrs)**	**Total Volume (ft^3)[b]**
Sufficient Capacity	21,836	38	-	-
Surcharged[a]	10,399	18	346	-
Insufficient Freeboard	10,107	17	-	-
Flooded	15,965	27	131	1,391,774

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits have insufficient freeboard or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

FIGURE 2-1
Task 2 Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



2.2.1 Baseline Improvements and Major Capacity Solutions

In the first watershed analyzed for this study, Hooffs Run, several baseline improvements and major capacity solutions were identified and addressed prior to evaluating solutions in the rest of the system. The goal of identifying baseline improvements was to remove hydraulic limitations that may have negatively affected the ability to model solutions. A similar evaluation was conducted for Taylor Run to determine whether baseline improvements and major capacity solutions were needed.

Profiles of the Taylor Run existing conditions model results were reviewed to identify significant changes in diameter or slope over relatively short distances where there was also a sudden increase in the hydraulic grade line (HGL). In addition to reviewing the profiles, the data sources for invert and diameter information were reviewed. There were no locations identified in the Taylor Run watershed that required baseline improvements. In addition, there were no locations identified within the Taylor Run watershed where extreme capacity limitations caused long backwater conditions and substantial flooding in the system. Therefore, there was no need for developing solutions for major capacity problems.

2.2.2 Alternative Solutions

The purpose of this task was to identify and evaluate corrective measures that could be undertaken to reduce flooding and improve stormwater quality through the use of green infrastructure practices. In addition, there is the potential to achieve other ancillary benefits such as improved aesthetics, urban heat island reduction, and carbon capture through context-sensitive solutions. Potential solutions were developed for each of the following project types or technologies, where applicable:

- Conveyance improvements
- Storage (modeled as underground storage, but could also be implemented as above ground storage or other conventional stormwater management approaches)
- GI

The goal of the conveyance solutions was to evaluate the impact of increased conveyance capacity on flooding and surcharge in the high-priority problem areas. Conveyance improvements were modeled in xpswmm by increasing pipe diameter up to 0.1-foot below ground surface (bgs). The invert elevations and alignment of existing pipes were not altered, so pipe slope did not change from existing conditions. Because the goal of this evaluation was not to design solutions but to evaluate potential strategies and technologies, more detailed design will be required to develop fully implementable projects, including adjusting pipe shapes, providing parallel pipes, and providing for adequate ground cover.

The storage solutions involved evaluating the potential for new detention or retention facilities or offline storage for high-priority problem areas. Because of the dense urban development prevalent in the City of Alexandria, conventional SWM practices were assumed in the hydraulic model to be limited to offline subsurface storage facilities. Opportunities for subsurface storage were identified in open spaces such as parking lots, green spaces, and grassed medians, with a preference for City-owned properties. Storage was modeled in xpswmm using storage nodes and weirs to model the overflow from a manhole into storage. The maximum storage size was determined by measuring the surface area of the open space available for storage and estimating the storage depth based on the manhole to which the storage system would be dewatered. It was assumed that storage should be a minimum of 3 feet deep and a maximum of 10 feet deep to maintain reasonable construction costs. Additionally, storage was only considered if gravity dewatering to a manhole within 1,000 feet was possible. Storage facilities would not be dewatered until the system had capacity to convey the stored flow. As such—and considering the focus of the modeling was to identify capacity limitations and flooding problems—storage dewatering was not evaluated in this analysis.

GI was evaluated at three different implementation levels: low, medium, and high. In the xpswmm model, GI was modeled by reducing impervious cover in model subcatchments. The low implementation level was modeled as a 10 percent reduction in impervious area, the medium at a 30 percent reduction, and the high at a 50 percent reduction. During development of the modeling approach soil and depression storage parameters were evaluated for sensitivity in the model. Ideally, these parameters would be adjusted to more accurately represent the physics of GI performance in the field. However, this level of detail in modeling was beyond the scope of this study, and infiltration parameters were not altered when modeling GI.

Table 2-4 describes the modeling approach and basic assumptions for each of the solution technologies. Solutions developed for each high-priority problem area are described in greater detail in the Solution Identification section of this report.

TABLE 2-4
Description of Solution Modeling Approaches and Assumptions
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Solution Technology/Strategy	Modeling Approach	Basic Assumptions
Conveyance	Increase Pipe Diameter	Use existing slope and pipe alignment. Increase pipe diameter to a maximum of 0.1-foot bgs. Add barrels as necessary.
Storage	Add storage node with weir to convey flow into storage	Storage depth is between 3 feet and 10 feet bgs. Gravity dewatering is required. A 20-foot-long weir to storage with discharge coefficient of 3 is required. Only surcharged flow will be sent to storage.
Green Infrastructure	Decrease catchment impervious area	Low implementation: 10 percent reduction in impervious area. Medium implementation: 30 percent reduction in impervious area. High implementation: 50 percent reduction in impervious area.

Solution alternatives were modeled in xpswmm. The basis for the solution models was the Task 2 existing conditions model.

Alternative solutions were evaluated in five different models, one for each technology/strategy:

- Conveyance solutions model
- Storage solutions model
- Low GI implementation model
- Medium GI implementation model
- High GI implementation model

This approach has limitations because several projects are in proximity to one another; therefore, the hydraulics are inextricably linked. However, because of the number of solutions and technologies being evaluated, evaluating each project independently was not within the scope of the analysis.

SECTION 3

Problem Identification

The purpose of the problem identification task was to assign a score to structures in the stormwater drainage network so that high-priority problem areas could be identified. Solution alternatives were developed for high-priority problem areas in the Taylor Run watershed. Junctions were scored for each of the problem area evaluation criteria. Table 3-1 shows the distribution of scores across the 1,006 stormwater junctions that were modeled in Taylor Run. The results were generated using the Task 2 existing condition model (existing IDF, existing boundary conditions). A map of the junction scores is provided on Figure 3-1.

TABLE 3-1
Taylor Run Problem ID Scores
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem ID Score	Count of Junctions	% of Total
0	493	49
0.1 – 20	333	33
20.1 – 30	105	10
30.1 – 40	58	6
40.1 – 50	17	2
>50	0	0
Total	1006	**100%**

After scoring individual junctions, high-priority problem areas were identified as groupings of hydraulically connected junctions and pipes in proximity to one another. A total of 12 high-priority problem areas were identified and are shown on Figure 3-2.

FIGURE 3-1
Taylor Run Problem Identification Score Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

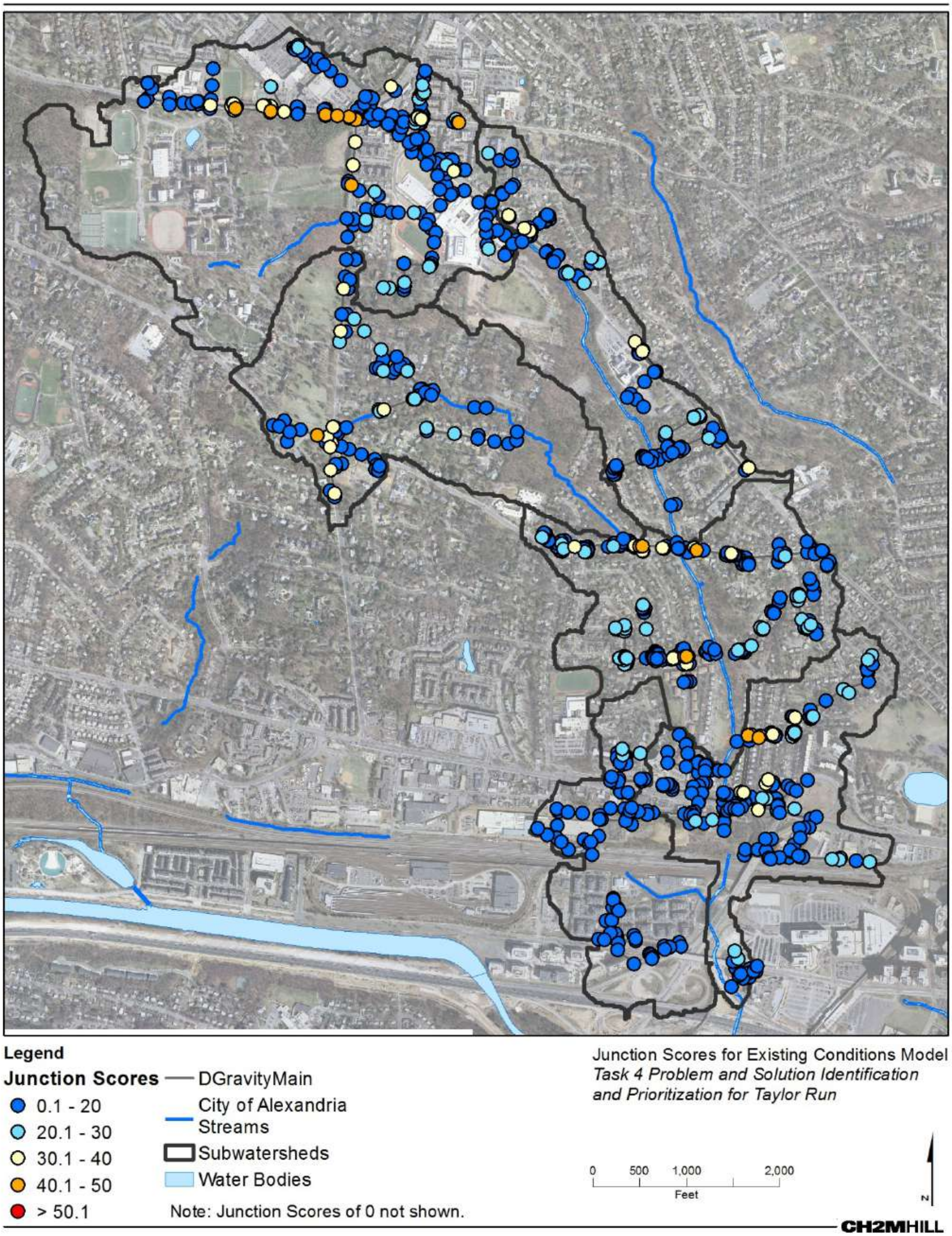
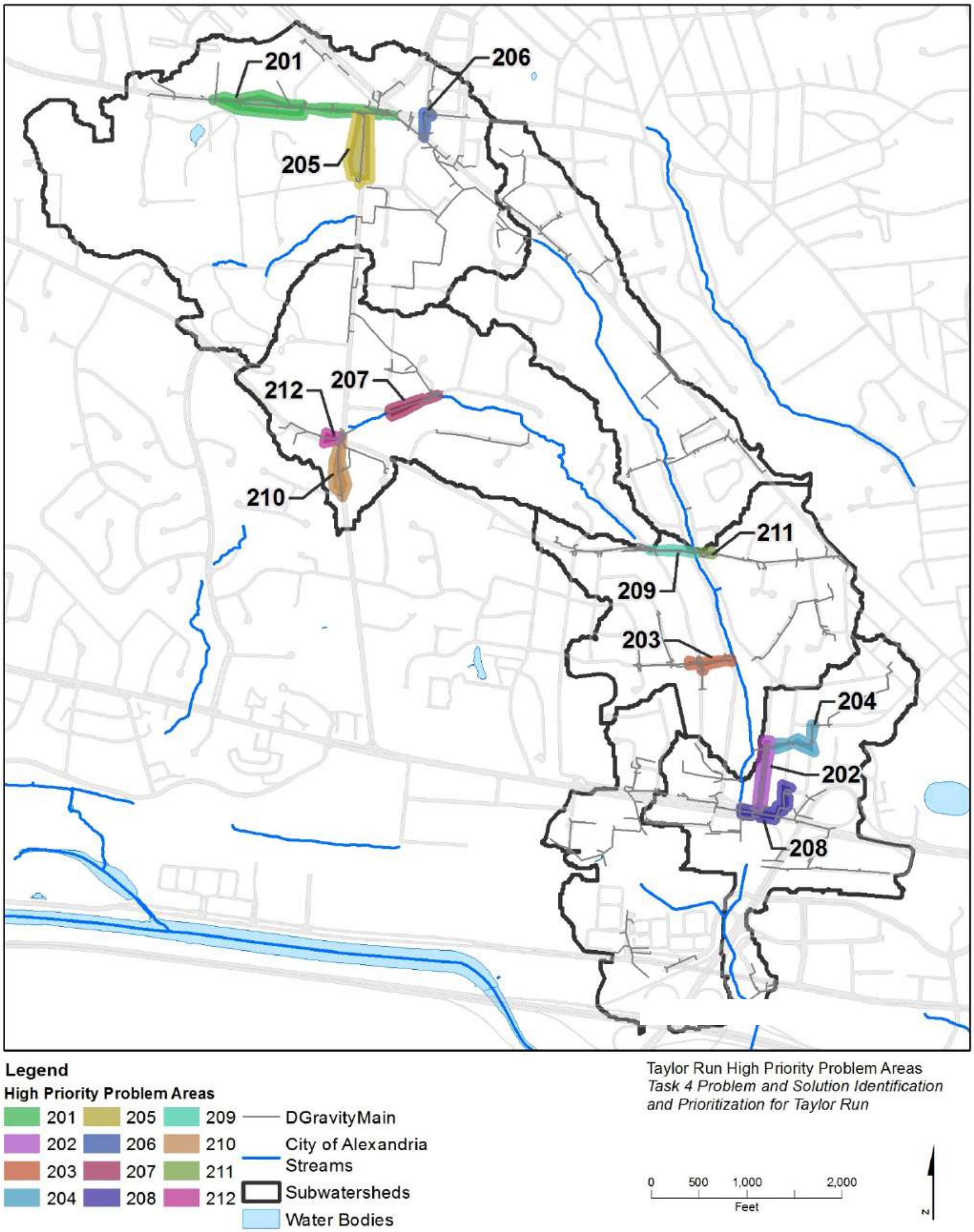


FIGURE 3-2
Location of Taylor Run High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



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SECTION 4

Solution Identification

A suite of solutions, including conveyance, storage, and GI projects, was developed for each problem area. The solution identification process resulted in 56 unique projects for the 12 high-priority problem areas in the Taylor Run watershed. Solutions were focused on the high-priority problem areas, therefore flooding outside those problem areas would not necessarily be addressed by any of the alternatives. For example, in Figure 4-1, there are segments of pipes located north of Problem Area 207 that experience some flooding but the Problem ID scores for this area are lower than the 30 point threshold. There is no critical infrastructure in the area, no public or staff identification of the problem and there is overland relief. Hence solutions were not developed for this area. The following text describes the specific solutions developed for each problem area by project type, as well as the model results.

4.1 Conveyance Solutions

A conveyance solution was developed for each of the high-priority problem areas. The goal of the conveyance solutions was to remove hydraulic limitations in the drainage network by increasing the capacity of the pipes in high-priority problem areas. Because this was a high-level conceptual exercise rather than a design exercise, the pipe alignment and roughness were left unchanged and capacity was increased solely by increasing the pipe size. In most cases, pipe shape was not altered except where sufficient capacity could not be achieved because of limited cover or where the existing pipe was a special shape, such as horizontal elliptical pipes. Where there was limited cover, circular pipes were changed to box culverts so that capacity could be increased without daylighting. Special pipe shapes were converted to equivalent-diameter circular pipes to simplify the model and calculations.

The conveyance capacity required was estimated using xpswmm. A hydraulic model was used to approximate the unconstrained peak flow in each pipe segment by upsizing pipes to 0.1-inch bgs to maximize diameter without daylighting the pipe, and by increasing the number of barrels by a factor of 2 across the board. The resulting unconstrained peak flow and Manning's equation were used to back-calculate the diameter required for the pipe to flow less than 80 percent full.

In the high-priority problem areas, the required diameter was compared to the existing diameter. Pipes that were smaller than the required pipe size calculated using the unconstrained peak flow were upsized and included in the conveyance project. Pipes that had sufficient capacity under existing conditions were left unchanged. Pipe size was not optimized during this exercise, and runs of pipes were not consistently sized. A summary of the length of pipe and range of pipe sizes included in each conveyance solution is included in Table 4-1. A table documenting the existing and proposed diameter of each pipe segment is provided in Appendix A.

TABLE 4-1
Summary of Conveyance Projects
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Project ID	Replacement Pipe Size Range and Project Description	Length (LF)
201	CONV-201	18-78 Inch Replacement Sewer Pipe Relief	2,286
202	CONV-202	18-30 Inch Replacement Sewer Pipe Relief	1,492
203	CONV-203	24-48 Inch Replacement Sewer Pipe Relief	539
204	CONV-204	30-60 Inch Replacement Sewer Pipe Relief	687
205	CONV-205	36-54 Inch Replacement Sewer Pipe Relief	726
206	CONV-206	18-36 Inch Replacement Sewer Pipe Relief	355

TABLE 4-1
Summary of Conveyance Projects
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Project ID	Replacement Pipe Size Range and Project Description	Length (LF)
207	CONV-207	48-48 Inch Replacement Sewer Pipe Relief	546
208	CONV-208	18-48 Inch Replacement Sewer Pipe Relief	730
209	CONV-209	30-90 Inch Replacement Sewer Pipe Relief	469
210	CONV-210	24-30 Inch Replacement Sewer Pipe Relief	313
211	CONV-211	36-54 Inch Replacement Sewer Pipe Relief	221
212	CONV-212	30-42 Inch Replacement Sewer Pipe Relief	184

A map of the results of the existing conditions model results is provided on Figure 4-2 for reference, and a map of the conveyance solution model results is provided on Figure 4-3. A summary of the results is provided in Table 4-2.

FIGURE 4-1
Existing Condition Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

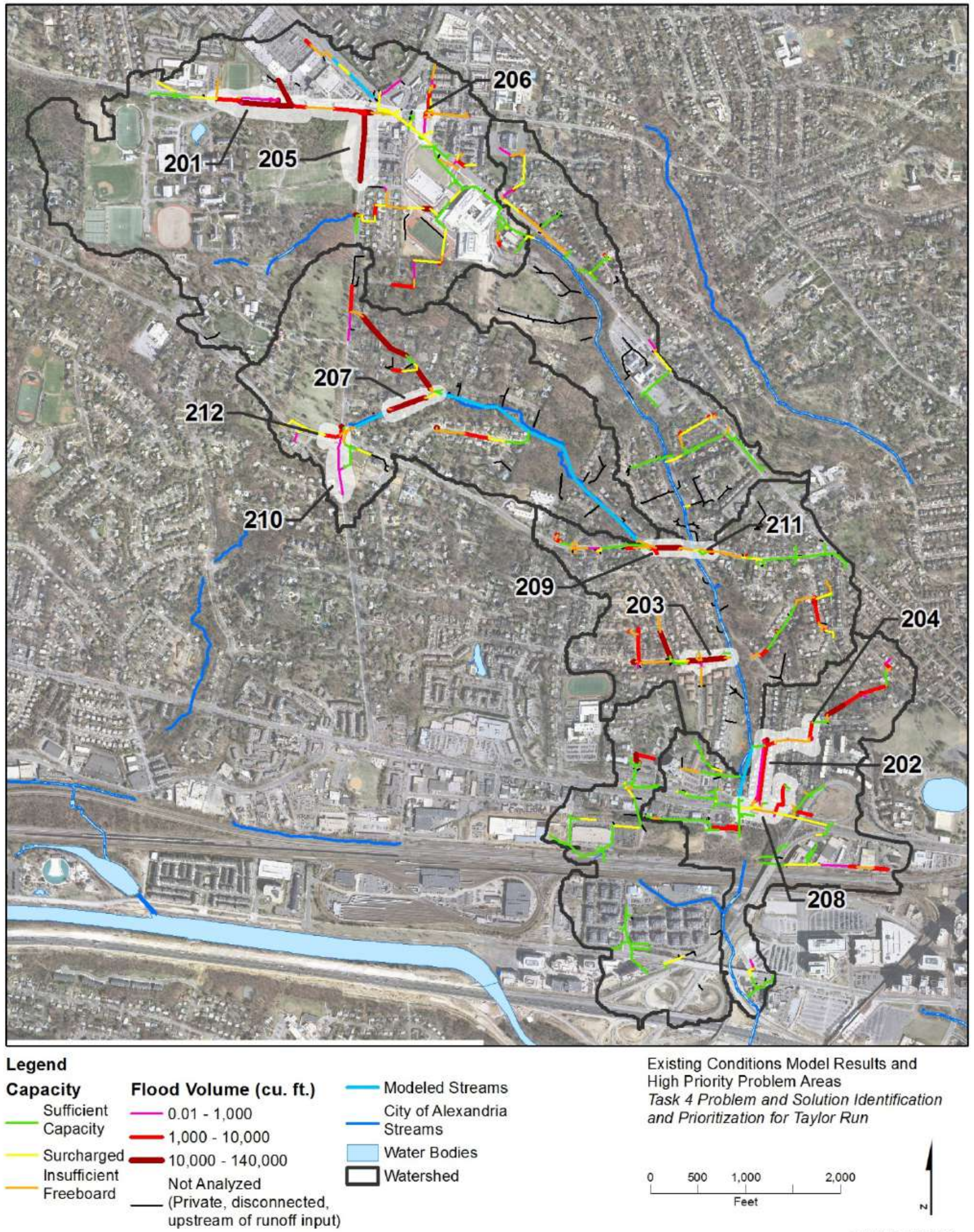
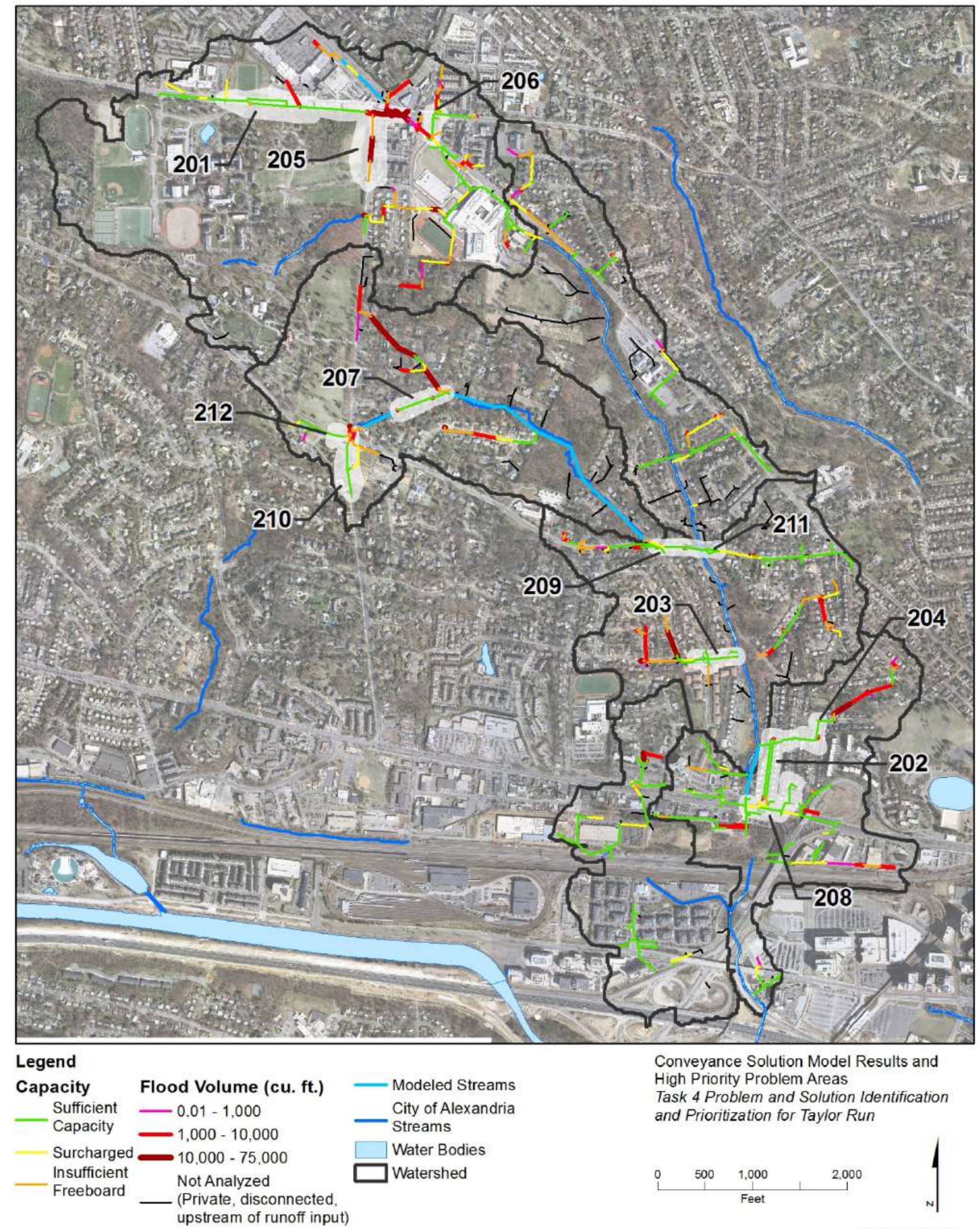


FIGURE 4-2
Conveyance Solutions Model Results and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



The conveyance solutions lessened and/or resolved most of the localized problems within the high-priority problem areas. In Taylor Run there is a limited amount of collection system downstream of the high-priority problem; however, the increased peak flow could have detrimental effects on the stream channel downstream. Table 4-2 summarizes the model results for the existing condition and the conveyance solutions models. Comparing the two results shows that overall flooding is eliminated in about 8 percent of the system by length. The total volume flooded is reduced by about 34 percent, and the duration of surcharge and flooding are reduced by 32 and 37 percent, respectively.

TABLE 4-2
Summary of Existing Conditions and Conveyance Solution Model Results in Taylor Run
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Existing Conditions Results				Conveyance Solutions Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	21,836	38	-	-	30,715	53	-	-
Surcharged[a]	10,399	18	346	-	8,605	15	236	-
Insufficient Freeboard	10,107	17	-	-	8,112	14	-	-
Flooded	15,965	27	131	1,391,774	10,877	19	82	926,470

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

Flooding outside of the high-priority problem areas was not addressed by the proposed solutions, therefore a summary of the modeling results within the high-priority problem areas is provided in Table 4-3. The overall flood volume across all 12 problem areas was reduced by 79 percent and the average reduction in flood volume in the 12 problem areas was 93%, as shown in Table 4-3. The disadvantage of conveyance solutions is that, although increasing pipe capacity reduces flooding in the problem area, it increases peak flow discharged from the problem area, which may increase peaks in the stream channel or cause new or additional flooding downstream. Implementing conveyance projects increased peak flow for all 12 high-priority problem areas, although this increase was much higher in some problem areas, ranging from a 24 percent increase in Problem Area 210 to a 281 percent increase in Problem Area 205.

TABLE 4-3
Conveyance Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
Problem Area ID	Existing Conditions Model Results	Conveyance Solution Model Results	Percent Reduction	Existing Conditions Model Results	Conveyance Solution Model Results	Percent Increase
201	1.839	0.678	63	155	330	113
202	0.266	0.057	79	19	31	63
203	0.953	-	100	26	81	208
204	0.084	-	100	58	86	48
205	1.370	0.414	70	30	119	305
206	0.102	-	100	25	49	98
207	0.410	-	100	49	135	176
208	0.121	-	100	71	117	64

TABLE 4-3
Conveyance Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
Problem Area ID	**Existing Conditions Model Results**	**Conveyance Solution Model Results**	**Percent Reduction**	**Existing Conditions Model Results**	**Conveyance Solution Model Results**	**Percent Increase**
209	0.233	-	100	454	599	32
210	0.010	-	100	30	37	24
211	0.128	-	100	72	102	42
212	0.058	-	100	36	47	29
		Average	**93**			**105**

Notes:
MG = million gallons
cfs = cubic feet per second

Taking the approach of sizing the conveyance projects based on the unconstrained peak flow allowed all conveyance projects to be run in a single iteration. Because stormwater gravity main diameters were increased to convey the largest potential peak flow, the impact of increasing capacity upstream was incorporated into the sizing of any downstream conveyance solutions. However, evaluating all of the conveyance projects in a single model run has several limitations. Because the problem areas are interconnected, modeling all solutions in a single run does not allow each solution to be viewed independently.

4.2 Storage Solutions

Conventional SWM solutions considered in this study include detention facilities and ordinance changes. Because of the challenges of translating ordinance changes into hydrologic and hydraulic parameters, only storage solutions were modeled in xpswmm. Ordinance changes were reviewed during the Hooffs Run Task solutions analysis and are summarized in *Task 4: Problem and Solution Identification and Prioritization for Hooffs Run, Alexandria, Virginia* (CH2M HILL, 2016b).

The goal of storage solutions was to add storage to the stormwater drainage network to decrease peak flow and volume during the modeled rainfall event. Because of the urban nature of the study area, it was assumed that to provide a sufficient storage volume, detention facilities would have to be belowgrade vaults. Several constraints guided the siting of potential storage solutions, including:

- Depth of storage facility should not exceed 10 feet to minimize excavation costs.
- Storage will be dewatered by gravity to a manhole less than 1,000 feet downstream to eliminate pumping costs.
- Minimum storage depth should be 3 feet, measured from the storage inlet to the storage outlet.
- Only surcharged flow will be sent to storage.

The first step in developing storage solutions was to identify open space that may be available for subsurface storage vaults with preference for City-owned property. This primarily included parking lots, green space (for example, parks, school yards, playing fields, church yards), and grassed medians or boulevards. These opportunities were identified using aerial imagery and were deemed feasible using drainage network data (gravity main locations and inverts) and topographic data. Storage areas meeting the constraints described above were identified for eight of the high-priority problem areas; no storage opportunities were identified for Problem Areas 202, 204, 207, or 211; two storage areas were identified in Problem Area 206. A map of these locations is provided on Figure 4-3, and Table 4-4 summarizes the storage depth, area, and volume. More details of the storage solution locations are provided in Appendix B.

FIGURE 4-3
Storage Solution Locations and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

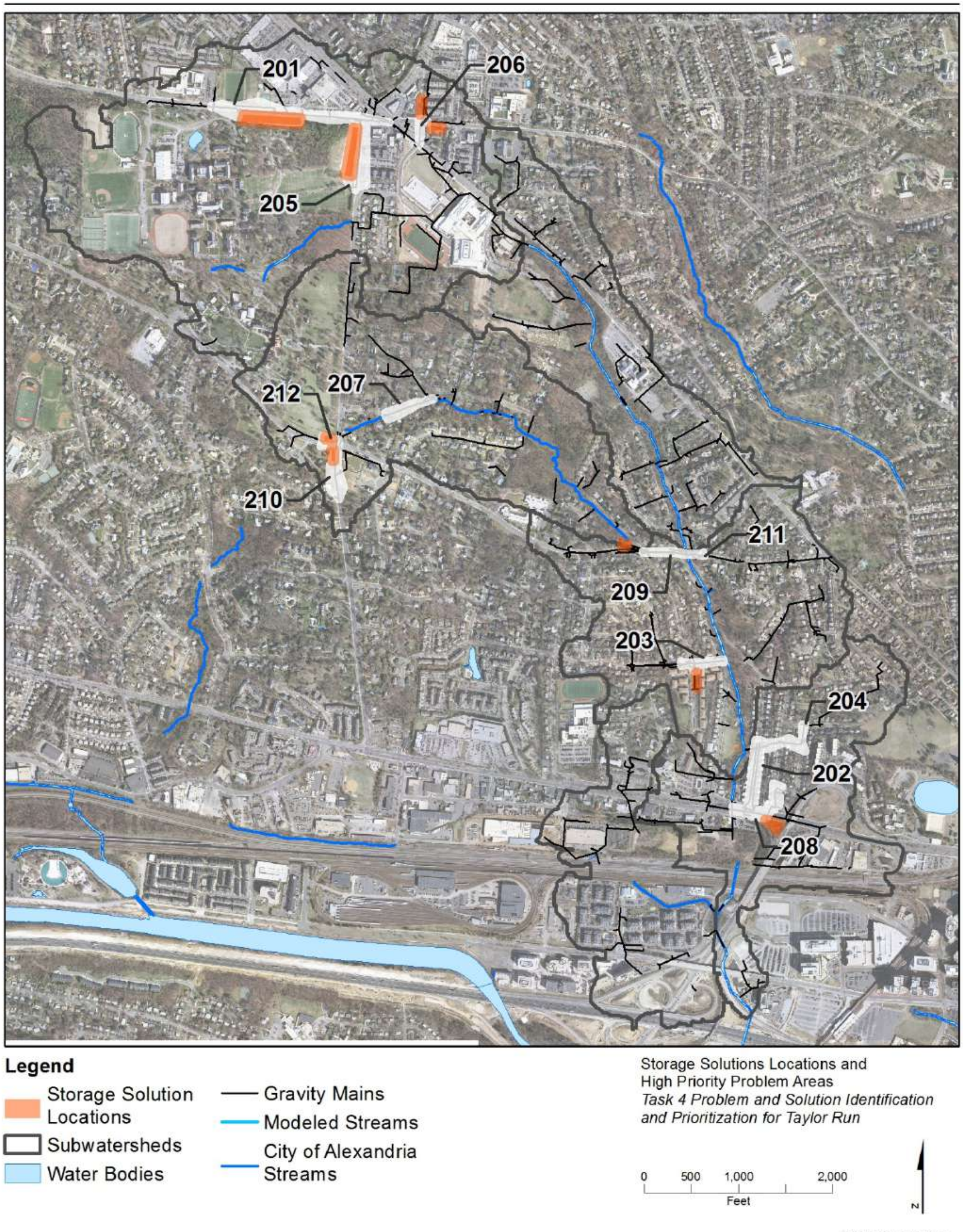


TABLE 4-4
Storage Solutions Summary
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Storage ID	Max Depth (ft)	Total Storage Area Available (ft^2)	Total Volume Available (ft^3)	Total Volume Required (ft^3)
201	12	10.0	50,227	502,273	18,448
203	4	9.6	2,623	25,144	11,503
205	13	9.4	35,434	332,445	128,493
206	11a	5.1	5,291	26,798	17,880
206	11b	10.0	4,554	45,537	4,031
208	1	6.4	8,134	52,140	27,495
209	5	8.7	2,651	23,086	3,027
210	8	10.0	4,482	44,823	4,131
212	9	6.2	3,514	21,947	15,030

No storage opportunities were identified for Problem Area 202, 204, 207, or 211.

A map of the results of the storage solution model run is provided on Figure 4-4, and a summary of the results is provided in Table 4-5.

FIGURE 4-4
Storage Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

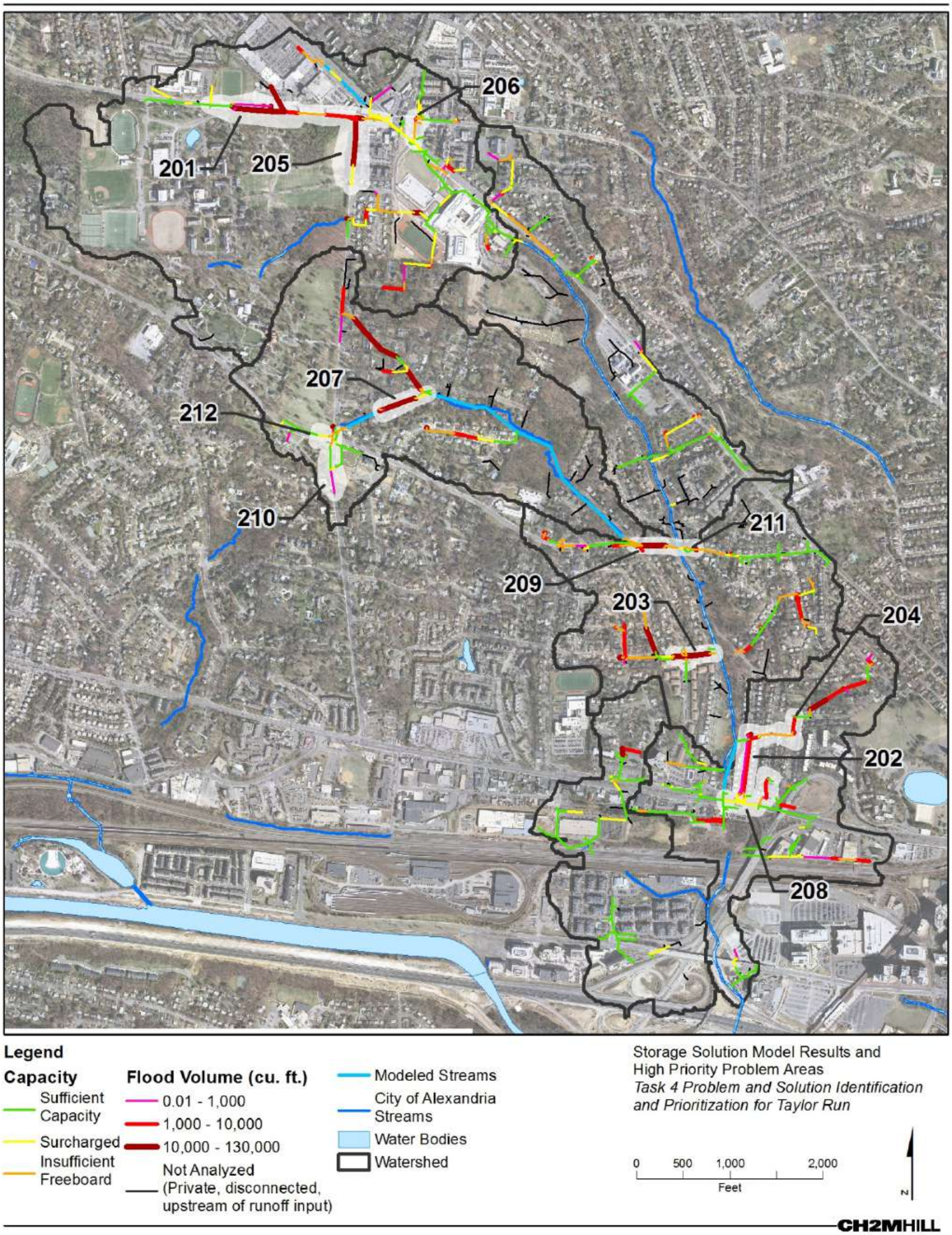


TABLE 4-5
Summary of Existing Conditions and Storage Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Existing Conditions Results				Storage Solutions Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft³)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft³)[b]
Sufficient Capacity	21,836	38	-	-	25,118	43	-	-
Surcharged[a]	10,399	18	346	-	10,063	17	320	-
Insufficient Freeboard	10,107	17	-	-	9,092	16	-	-
Flooded	15,965	27	131	1,391,774	14,036	24	115	1,215,837

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.

[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.

[b] Flooded volume includes volume flooded at upstream end of the conduit.

Overall, the storage solutions eliminates almost 13 percent of the total volume of flooding in the watershed and the duration of flooding is reduced by about 12 percent. Flooding is eliminated in about 3 percent of the system by length and insufficient freeboard and surcharge are each reduced in about 1 percent of the system by length. These reductions in flooding, insufficient freeboard, and surcharge led to a 5 percent increase in pipes with sufficient capacity and the total duration of surcharge in the system is decreased by 8 percent.

Flooding outside of the high-priority problem areas was not addressed by the proposed solutions, therefore Table 4-6 summarizes the modeling results within the high-priority problem areas. On average, the flood volume and peak flow reductions within the high-priority problem areas are 36 and 6 percent, respectively.

TABLE 4-6
Storage Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
Problem Area ID	Existing Conditions Model Results	Storage Solution Model Results	Percent Reduction	Existing Conditions Model Results	Storage Solution Model Results	Percent Reduction
201	1.839	1.658	10	155.0	155.0	0
202	0.266	0.236	11	18.9	15.3	19
203	0.953	0.895	6	26.1	26.1	0
204	0.084	0.084	0	58.2	58.2	0
205	1.370	0.860	37	29.5	29.1	1
206	0.102	0.028	73	24.7	24.5	1
207	0.410	0.377	8	49.0	49.0	0
208	0.121	0.023	81	71.4	61.6	14
209	0.233	0.221	5	454.2	453.9	0

TABLE 4-6
Storage Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
Problem Area ID	**Existing Conditions Model Results**	**Storage Solution Model Results**	**Percent Reduction**	**Existing Conditions Model Results**	**Storage Solution Model Results**	**Percent Reduction**
210	0.010	0.000	100	17.4	16.8	3
211	0.128	0.128	0	71.9	71.9	0
212	0.058	-	100	36.1	24.2	33
		Average	**36**			**6**

Evaluating all of the storage solutions in a single model is not limited by increases in downstream impacts as the conveyance solutions are. Instead, because of the increased storage capacity at upstream problem areas, the full peak flow may not reach downstream problem areas. In this case, the performance of a problem area may appear to be more favorable than if each problem area were modeled separately. In general, the level of flood reduction realized with the storage solution was not significant compared to the conveyance solution.

4.3 Green Infrastructure Solutions

The goal of GI solutions is to reduce the peak runoff rate and runoff volume directed to the storm drainage system by converting impervious surfaces to pervious surfaces. This is accomplished in the field by redirecting runoff from impervious surfaces to GI facilities that detain and infiltrate runoff during rainfall events. Three levels of GI—low, medium, and high—were evaluated in this analysis. In the model, GI was evaluated by reducing the impervious cover in model subcatchments by 10 percent, 30 percent, and 50 percent to represent the low, medium, and high levels of implementation, respectively.

Several GI technologies were considered feasible within the City of Alexandria, including:

- **Bioretention/ Planters** – Planted depression or constructed box with vegetation that typically receives runoff from roadways or rooftops; includes vegetation and soil media over an underdrain and filtration fabric. The City does not typically encourage infiltration; therefore, rain gardens, which typically do not have an underdrain, are not encouraged.
- **Cisterns** – A tank for storing water, typically connected to a roof drain, that can be either above or below ground. Water from a cistern is typically reused or slowly infiltrated into the soil rather than discharged to a storm sewer.
- **Green/Blue Roofs** - A roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane (green roof) or a roof that is capable of storing and then slowly releasing rainwater (blue roof).
- **Porous Pavement** - Paving surfaces designed to allow stormwater infiltration; may or may not include underground storage component.
- **Surface Storage** – Retrofit of inlets and catch basins to include flow regulators on streets with a standard curb and gutter system so that stormwater can be stored within the roadway and slowly released back into the storm sewer system.
- **Amended Soils** – Altering soils to improve water retention, permeability, infiltration, drainage, aeration, and/or structure.

These technologies were grouped into GI programs based on the land uses where they could be applied. A program combines a set of technologies into an implementation strategy for different types of sites and land use categories. Programs being considered are described below.

- **Green Streets/Alleys** – Includes bioretention/planters and porous pavement combined along the public right-of-way (ROW) between buildings and roadways; can include parking lane and curb cuts.
- **Green Roofs** – Includes green/blue roofs, sometimes in combination with cisterns.
- **Green Schools** – Use of school properties to implement one-to-many GI management strategies, including bioretention/planters, cisterns, green/blue roofs, and porous pavement.
- **Green Parking** – Bioretention/planters and porous pavement in parking lots.
- **Green Buildings** – Use of bioretention/planters, cisterns, and/or downspout disconnection on public or private buildings.
- **Blue Streets** – Short-term surface storage on streets with relatively flat slopes and standard curb and gutter systems.
- **Open Spaces** – Use of open spaces to store and/or infiltrate stormwater using a combination of detention, amended soils, bioretention/planters, and/or porous pavement; may also include stream daylighting where appropriate.

Six GI concepts were developed for the Taylor Run watershed. These concepts, which are described in greater detail in Appendix C, demonstrate the applicability of GI technologies in the City of Alexandria.

A drainage area for each high-priority area was identified using the model's hydrologic subcatchments. Because the drainage area includes all model subcatchments upstream of the problem area, where there are problem areas upstream of one another, drainage areas overlap. A map of these drainage areas and problem area locations is provided on Figure 4-5, and Table 4-7 summarizes the drainage area, existing impervious area, and impervious area for each level of GI implementation.

FIGURE 4-5
Green Infrastructure Drainage Areas and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

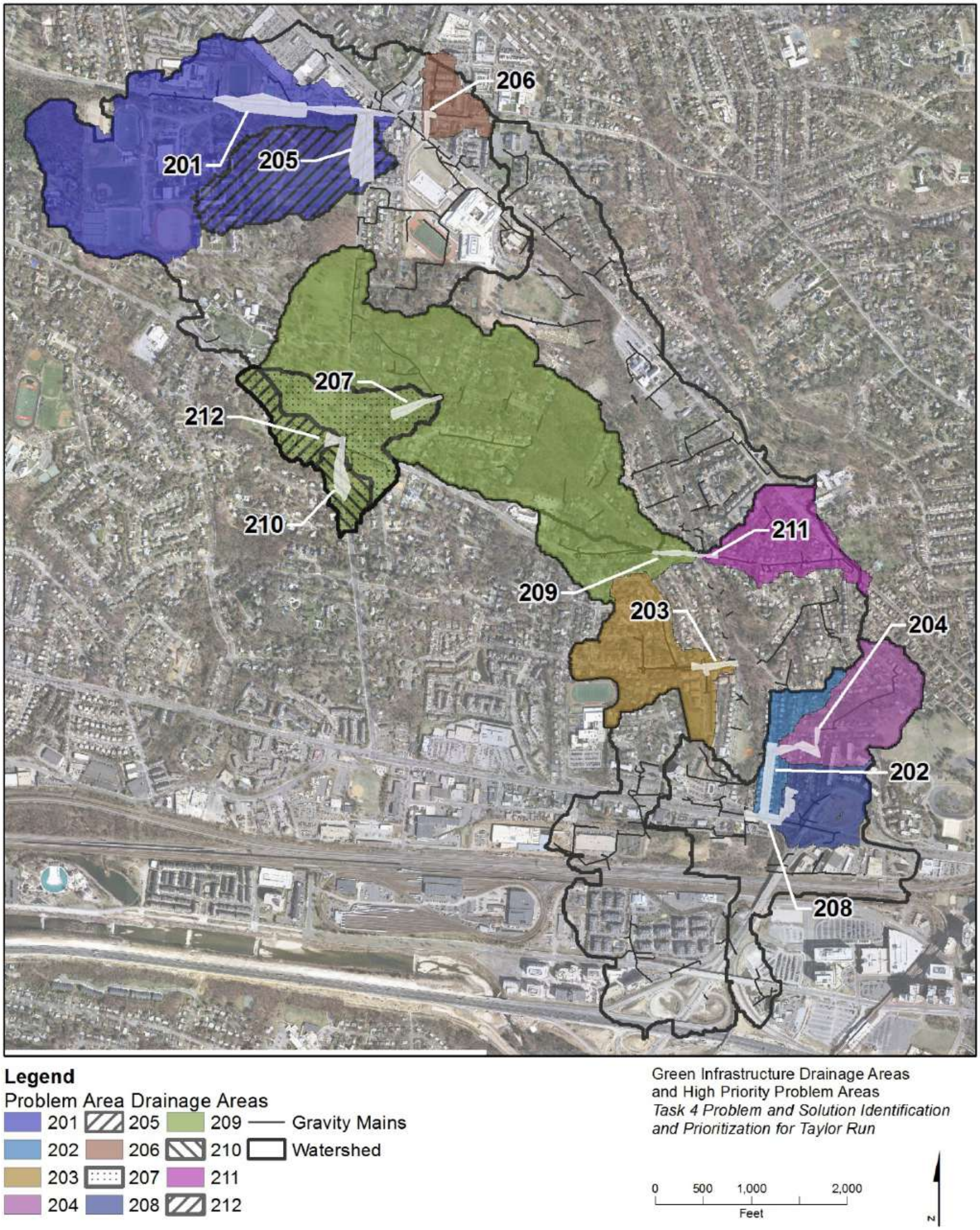


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TABLE 4-7
Green Infrastructure Solutions Summary
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

			Green Infrastructure Solution Impervious Area (acres)		
Problem Area ID	**Drainage Area (acres)**	**Existing Impervious Area (acres)**	**Low Implementation**	**Medium Implementation**	**High Implementation**
201	129.7	35.3	31.8	24.7	17.7
202	10.0	3.9	3.5	2.8	2.0
203	31.8	13.3	12.0	9.3	6.7
204	26.5	8.4	7.6	5.9	4.2
205	35.1	7.7	6.9	5.4	6.8
206	10.0	6.7	6.0	4.7	3.4
207	38.5	10.5	9.4	7.3	5.2
208	16.9	6.6	6.0	4.7	3.3
209	172.9	40.3	36.3	28.2	20.1
210	6.8	2.2	2.0	1.5	1.1
211	22.4	9.3	8.3	6.5	4.6
212	8.6	3.1	2.8	2.1	1.5

Maps of the results of the low, medium, and high GI solutions are provided on Figures 4-6 through 4-8, and a summary of the model results is provided in Table 4-8.

FIGURE 4-6
Low-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

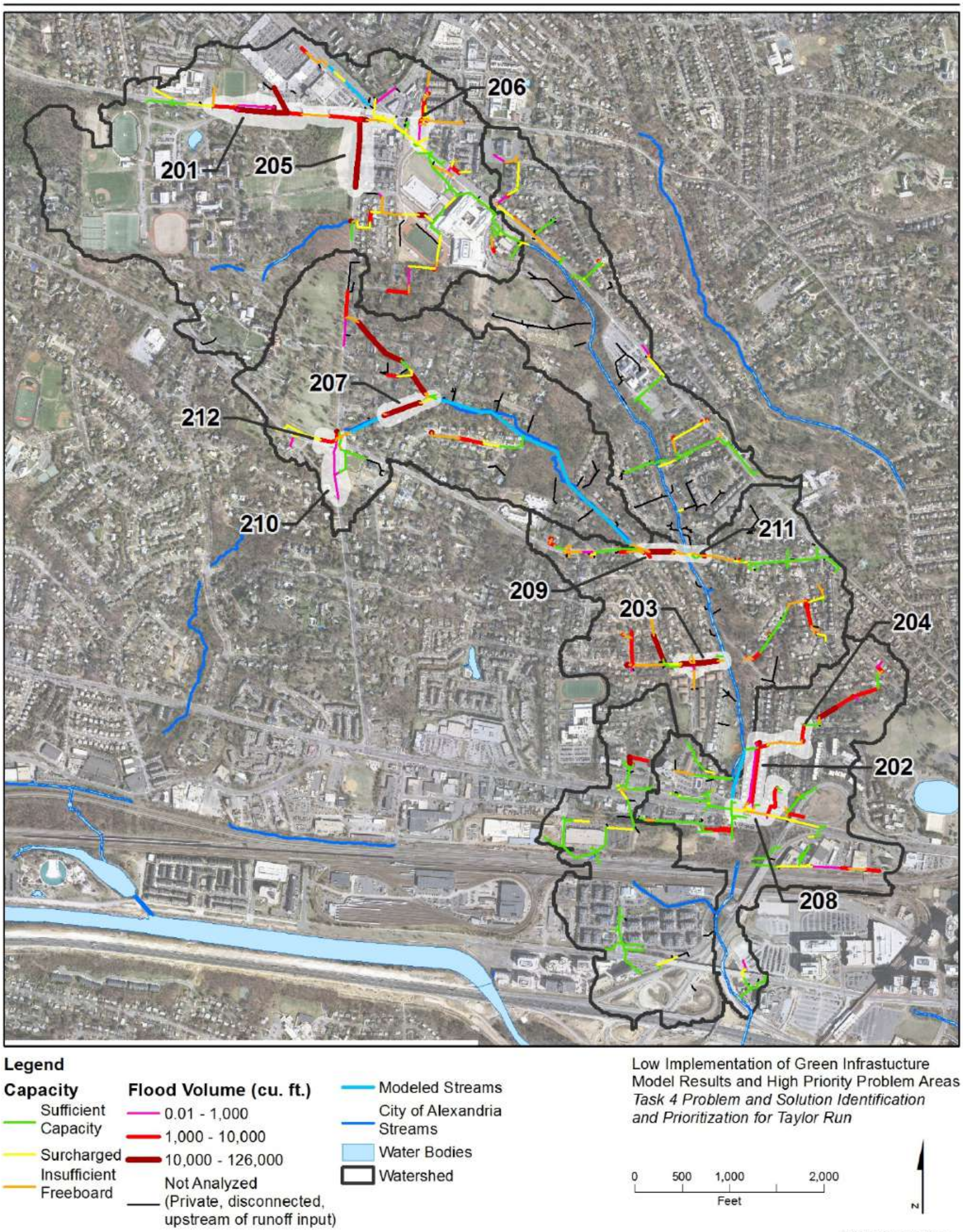


FIGURE 4-7
Medium-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

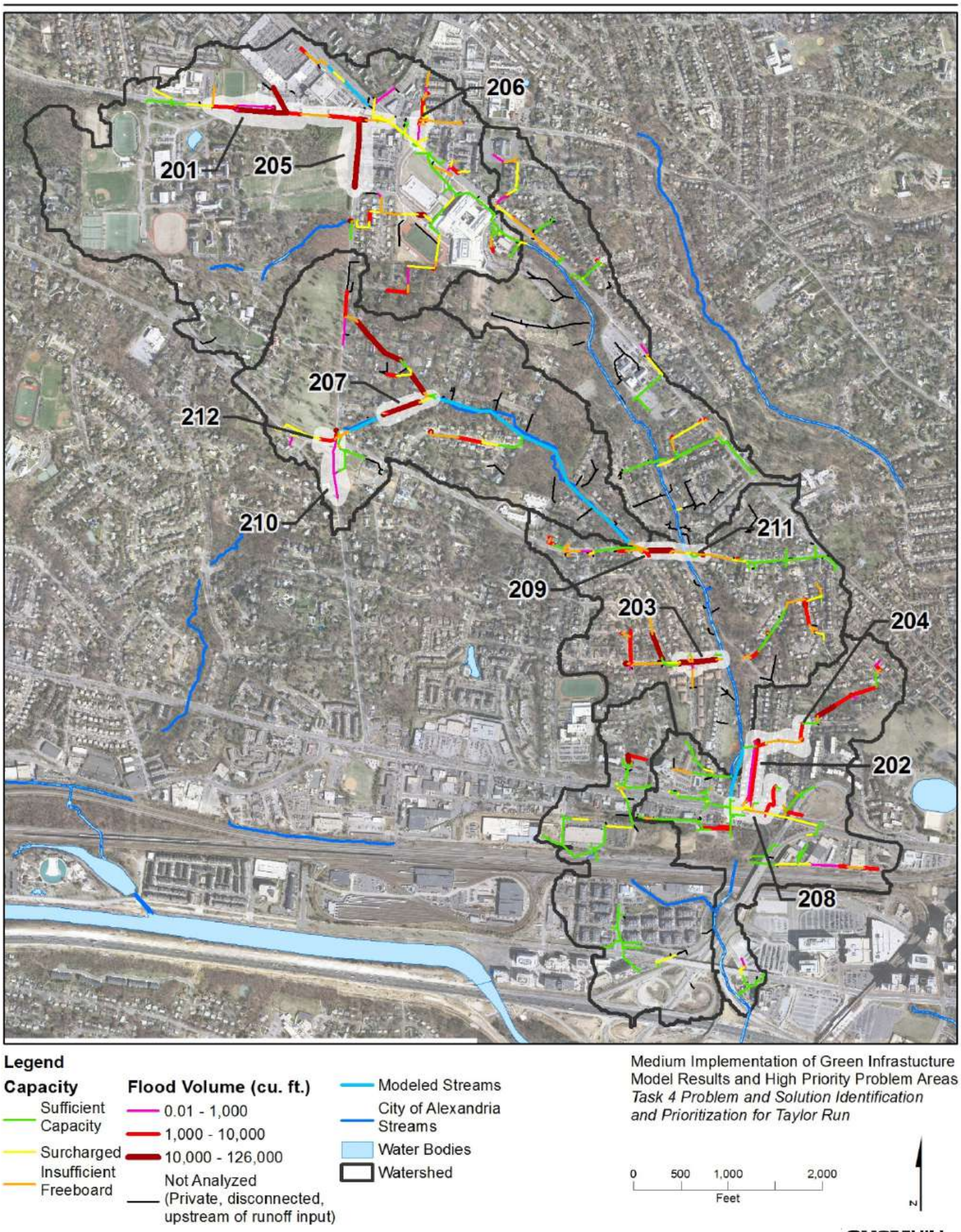


FIGURE 4-8
High-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

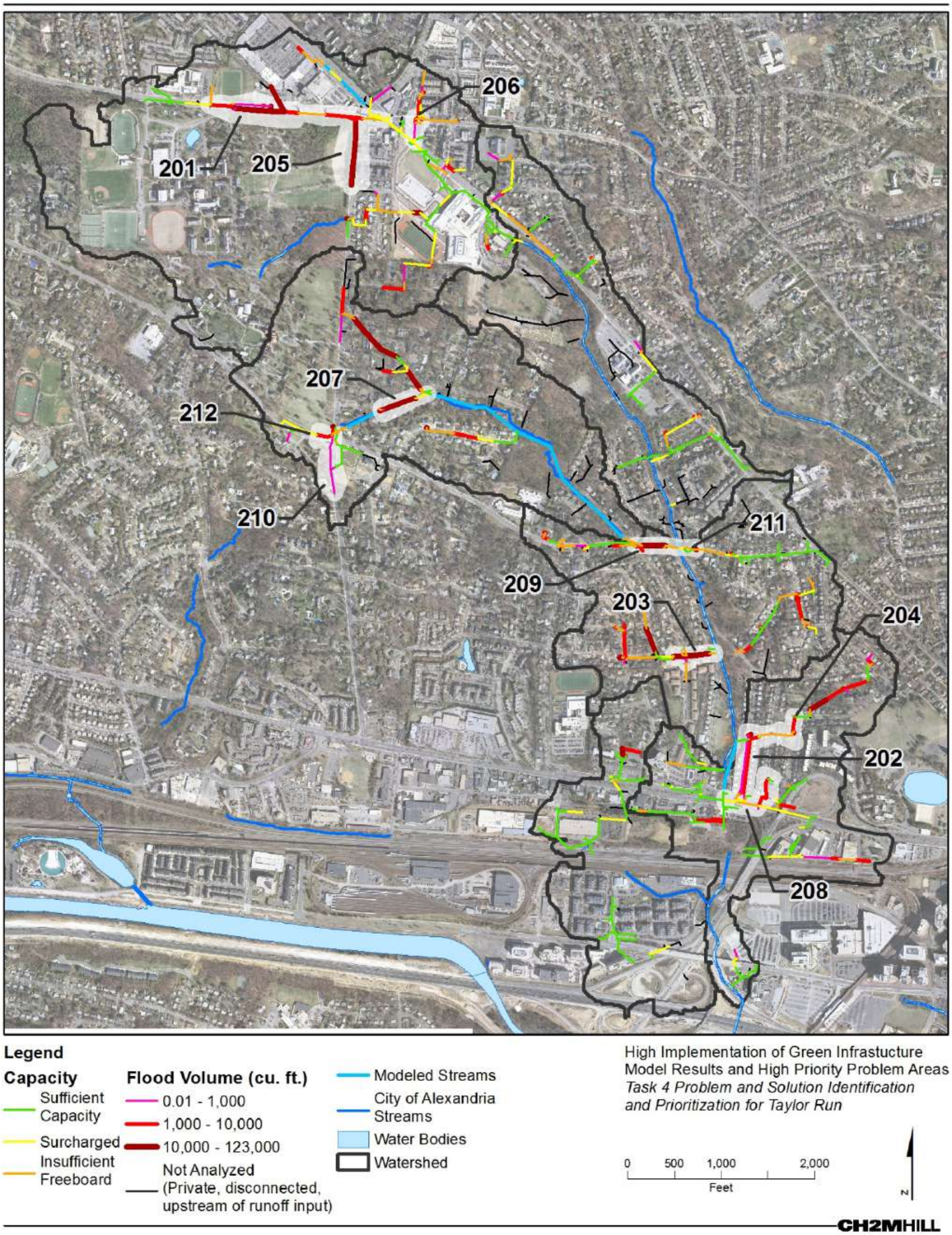


TABLE 4-8
Summary of Existing Conditions and Green Infrastructure Implementation Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Existing Conditions Results				Low Green Infrastructure Implementation Results				Medium Green Infrastructure Implementation Results				High Green Infrastructure Implementation Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	21,836	38	-	-	22,113	38	-	-	22,215	38	-	-	22,565	39	-	-
Surcharged[a]	10,399	18	346	-	10,198	17	343	-	10,096	17	331	-	9,833	17	322	-
Insufficient Freeboard	10,107	17	-	-	10,032	17	-	-	10,062	17	-	-	9,976	17	-	-
Flooded	15,965	27	131	1,391,774	15,965	27	129	1,371,480	15,935	27	126	1,331,539	15,935	27	122	1,291,598

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.

[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.

[b] Flooded volume includes volume flooded at upstream end of the conduit.

Overall, model results showed that GI is not effective at reducing flood volumes and durations in the Taylor Run storm sewer system. There was no significant change in the total length of pipes that are flooded across the various levels of GI implementation from 10 percent to 50 percent reduction in imperviousness. The GI solution was only effective at reducing the total volume and duration of flooding. At the high end, a 50 percent reduction in impervious area reduces total flood volume by about 7 percent, which is significantly less than what was achieved with the conveyance solution.

Flooding outside of the high-priority problem areas was not addressed by the proposed solutions, therefore results within each high-priority problem area are shown in Tables 4-9 and 4-10. On average, the flood volume was reduced by 2 percent in high-priority problem areas by the low GI implementation, 7 percent by the medium GI implementation, and about 11 percent by the high GI implementation solution. Peak flow results showed no change on average across the various levels of GI implementation.

TABLE 4-9
Green Infrastructure Solutions Flood Volume Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

		Low GI Implementation		Medium GI Implementation		High GI Implementation	
Problem Area ID	**Existing Condition Flood Volume (MG)**	**Solution Flood Volume (MG)**	**Percent Reduction**	**Solution Flood Volume (MG)**	**Percent Reduction**	**Solution Flood Volume (MG)**	**Percent Reduction**
201	1.839	1.788	3	1.689	8	1.578	14
202	0.266	0.263	1	0.257	4	0.250	6
203	0.953	0.934	2	0.901	5	0.889	7
204	0.084	0.083	1	0.080	5	0.078	8
205	1.370	1.351	1	1.315	4	1.281	6
206	0.102	0.100	2	0.096	6	0.093	9
207	0.410	0.407	1	0.400	2	0.394	4
208	0.121	0.120	2	0.116	4	0.113	7
209	0.233	0.227	3	0.216	7	0.205	12
210	0.010	0.010	5	0.008	18	0.007	29
211	0.128	0.125	2	0.118	8	0.111	13
212	0.058	0.056	3	0.053	10	0.049	16
		Average	**2**		**7**		**11**

TABLE 4-10
Green Infrastructure Solutions Peak Flow Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

		Low GI Implementation		Medium GI Implementation		High GI Implementation	
Problem Area ID	**Existing Condition Peak Flow (cfs)**	**Solution Peak Flow (cfs)**	**Percent Reduction**	**Solution Peak Flow (cfs)**	**Percent Reduction**	**Solution Peak Flow (cfs)**	**Percent Reduction**
201	155.0	154.9	0	154.7	0	154.5	0
202	18.9	19.0	0	19.2	-1	19.2	-1
203	26.1	26.1	0	26.0	0	25.9	1
204	58.2	58.2	0	58.2	0	58.1	0
205	29.5	29.4	0	29.5	0	29.5	0
206	24.7	24.7	0	24.7	0	24.6	0
207	49.0	49.0	0	49.0	0	48.9	0
208	71.4	71.4	0	71.3	0	71.3	0
209	454.2	453.7	0	452.8	0	451.7	1
210	17.4	17.4	0	17.3	0	17.4	0
211	71.9	71.9	0	71.8	0	71.7	0
212	36.1	36.0	0	35.9	0	35.8	1
		Average	**0**		**0**		**0**

SECTION 5

Alternatives Analysis and Prioritization

The goal of alternatives analysis and prioritization was to evaluate the cost and performance of the various solution approaches/technologies and develop watershed-wide alternatives aimed at resolving capacity-related problems in the Taylor Run watershed. The solution identification process resulted in 56 unique projects for the 12 high-priority problem areas in the Taylor Run watershed. The alternatives analysis and prioritization was performed after completing the solution modeling for the high-priority problem areas. The following section describes the results of the alternatives analysis and prioritization.

5.1 Problem Area Benefit Analysis

The 56 solutions for the 12 high-priority problem areas were scored for the 8 solution evaluation criteria:

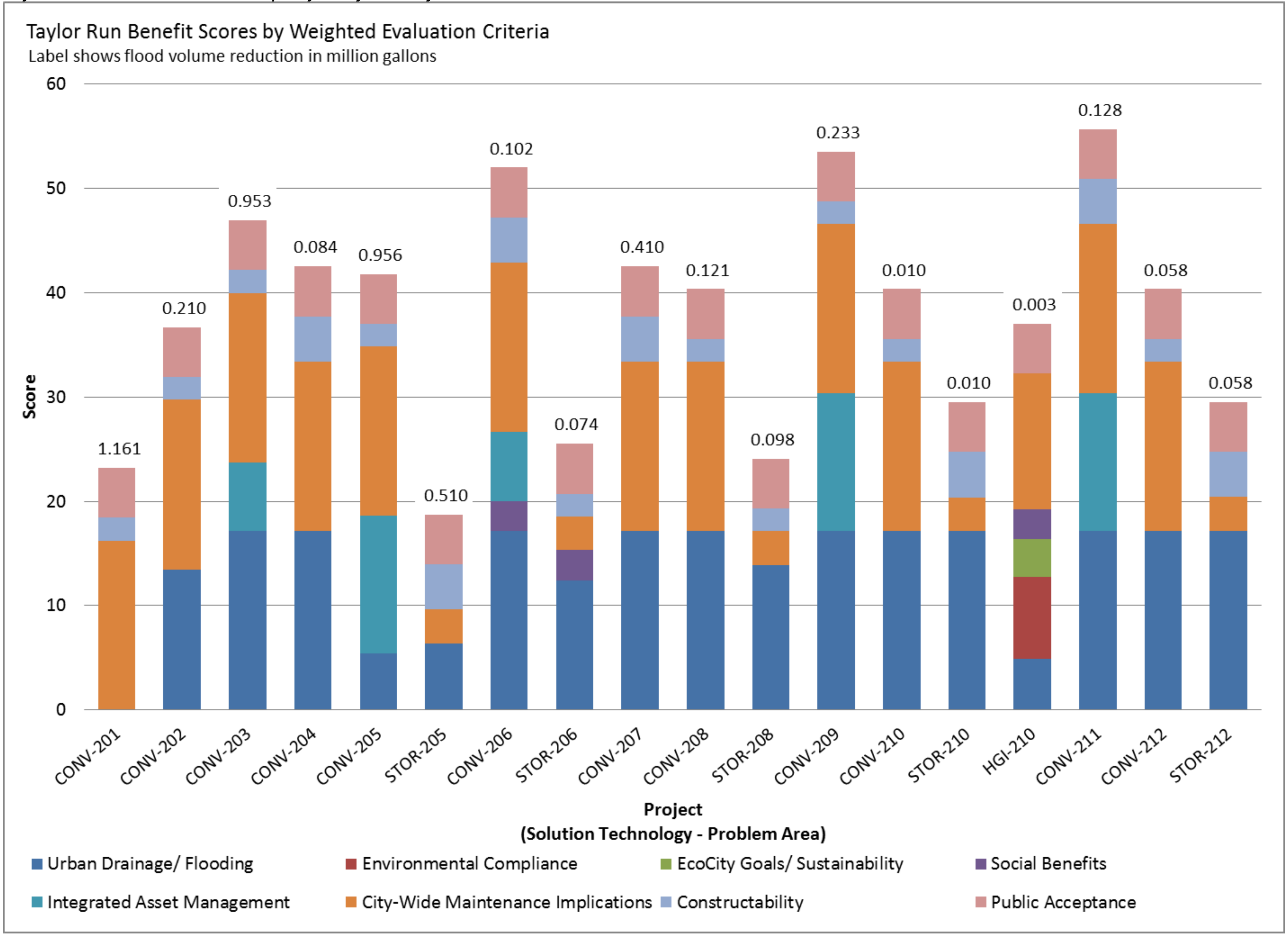
- Urban drainage/flooding
- Environmental compliance
- EcoCity goals/sustainability
- Social benefits
- Integrated asset management
- City-wide maintenance implications
- Constructability
- Public acceptability

After completing preliminary scoring of all projects, City staff reviewed prioritization results to be sure the objectives of the analysis were being met. This review resulted in a minimum flood reduction threshold of 22 percent for all projects. If projects did not meet this minimum threshold, they were not included in the prioritization, although the scoring and costing data were maintained for documentation. Because GI was not particularly effective in the Taylor Run watershed, nearly all of the GI solutions were eliminated by the minimum flood reduction threshold. Of the 56 solutions, 38 did not meet the minimum flood reduction threshold, leaving 18 projects.

Figure 5-1 is a bar chart of the total benefit scores for each of the 18 projects that meet the minimum threshold. The horizontal axis has the project name, which is a combination of the problem area number and the technology/solution approach type. For example, CONV-201 is the conveyance solution for problem area 201; STOR-201 is the storage solution; and LGI-201, MGI-201, and HGI-201 are the low, medium, and high GI implementations, respectively. The charts show all solutions included in the prioritization (that is, all solutions providing at least 22 percent reduction in flooding) by problem area in ascending order from left to right.

A full table of the scoring and alternatives analysis results is included in Appendix D.

FIGURE 5-1
Total Benefit Score Chart for High-priority Problem Areas 201 through 212
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



5.2 Problem Area Solution Costs

Planning-level capital costs, which include construction as well as engineering and design and contingency, were developed for each of the 56 solutions. The basis of the cost information for each technology is provided in Appendix E. The basic unit costs used for costing the various projects were the same across all City infrastructure projects. Three levels of GI implementation were evaluated for this project:

- High Implementation – Manage 50 percent of total impervious area in the watershed
- Medium Implementation – Manage 30 percent of total impervious area in the watershed
- Low Implementation – Manage 10 percent of total impervious area in the watershed

The unit cost of implementing GI at the various implementation levels is driven by the availability of GI opportunity areas. Because the GI opportunity areas varied across watersheds, the cost of implementation of the various levels of GI also varies across watersheds. Table 5-1 provides the construction cost assumptions for the low, medium, and high implementation levels of GI in the Taylor Run watershed based on implementing GI across the whole watershed.

TABLE 5-1
Taylor Run Green Infrastructure Construction Costs
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Area Managed			
Green Infrastructure Level	%	Ac	**Cost Per Acre Managed**	**Construction Cost**
Low Green Infrastructure	10	30.3	$44,508	$1,348,134
Medium Green Infrastructure	30	90.9	$82,368	$7,484,763
High Green Infrastructure	50	151.5	$89,662	$13,579,245

Table 5-2 provides the capital cost, in millions of dollars, for all 56 solutions. Projects that do not meet the minimum threshold for flood reduction are shown in ***bold italics***.

TABLE 5-2
Capital Costs for High-priority Problem Area Solutions
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area	Conveyance	Storage	Low Green Infrastructure	Medium Green Infrastructure	High Green Infrastructure
201	$1.80	***$0.30***	***$0.22***	***$1.22***	***$2.22***
202	$0.35	-	***$0.02***	***$0.14***	***$0.25***
203	$0.22	***$0.20***	***$0.08***	***$0.46***	***$0.84***
204	$0.37	-	***$0.05***	***$0.29***	***$0.53***
205	$0.39	$1.91	***$0.05***	***$0.27***	***$0.48***
206	$0.24	$0.38	***$0.04***	***$0.23***	***$0.42***
207	$0.34	-	***$0.07***	***$0.36***	***$0.66***
208	$0.30	$0.43	***$0.04***	***$0.23***	***$0.42***
209	$0.56	***$0.07***	***$0.25***	***$1.39***	***$2.53***
210	$0.10	$0.09	***$0.01***	***$0.08***	$0.14
211	$0.13	-	***$0.06***	***$0.32***	***$0.58***
212	$0.08	$0.25	***$0.02***	***$0.11***	***$0.19***
Total	**$4.89**	**$3.61**	**$0.92**	**$5.09**	**$9.24**

Note:
Costs shown in ***bold italics*** are for projects that do not meet the 22 percent minimum flood reduction threshold set by the City.
Costs are in millions of dollars.

5.3 Problem Area Benefit/Cost Results

The benefit/cost score is the ratio of the total benefit divided by the total capital cost in millions of dollars. This metric indicates the cost efficiency of a project and can help direct resources to the projects that will provide the greatest benefit for the lowest cost. Cost benefit results are presented on Figure 5-2. The chart shows only those projects meeting the 22 percent minimum flood reduction threshold and are presented by problem area in ascending order from left to right on the horizontal access.

The benefit/cost score is shown as a bar chart in blue. Additionally, the cost per gallon of flood reduction is included as a line on a logarithmic scale with the exact cost/gallon of flood reduction shown in a text label. This metric provides an alternative cost-based method for ranking projects. It is important to remember that the best projects will have a high benefit/cost score but a low cost per gallon of flood reduction.

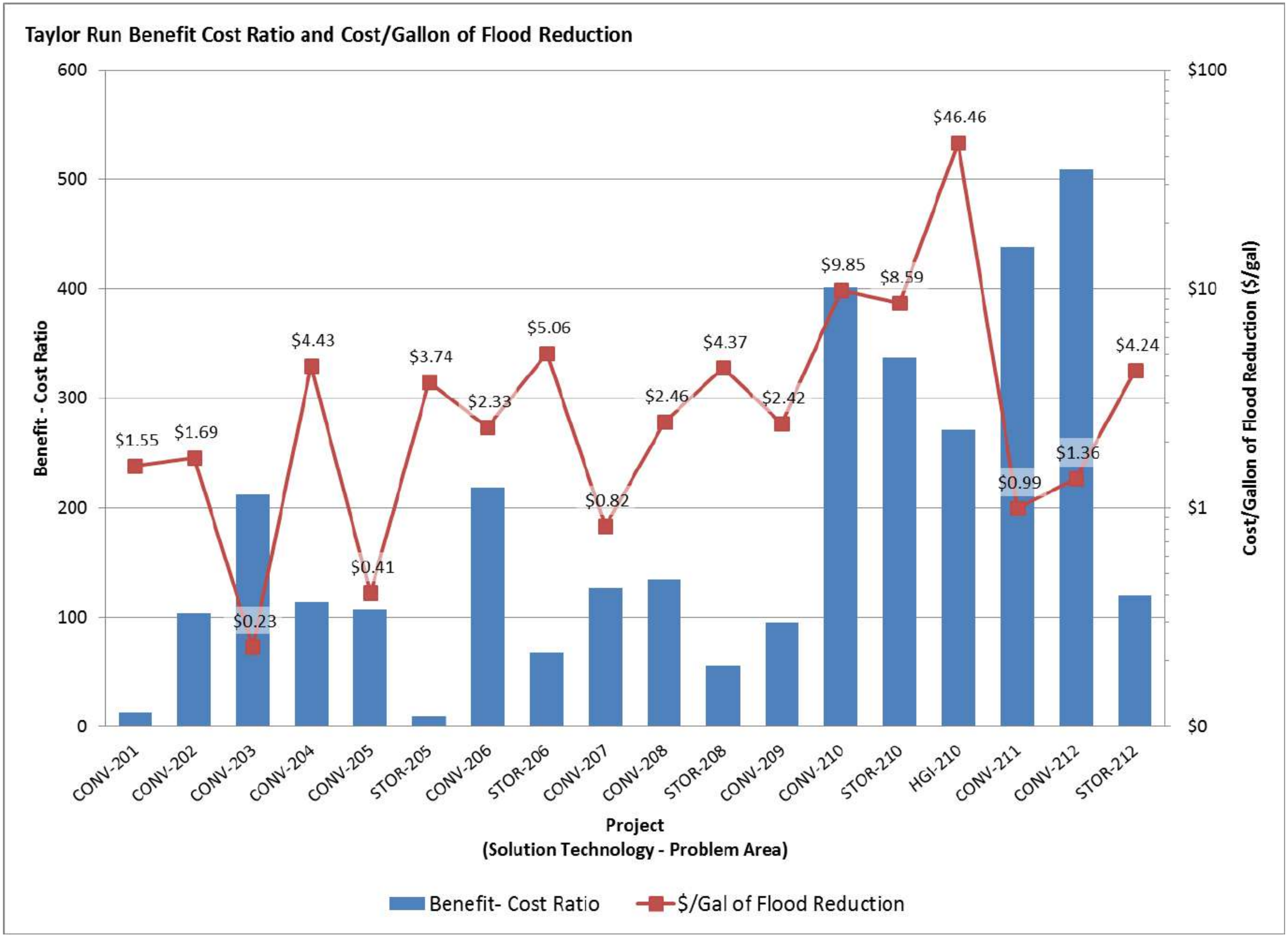
5.4 Watershed-wide Alternatives

Three watershed-wide alternatives were developed for Taylor Run. Each watershed-wide alternative was aimed at resolving capacity-related issues while also meeting a second goal: including maximizing cost-efficiency or benefit cost, or targeting the highest-priority problems. The three alternatives examined include:

- Alternative 1: Most cost-effective solution for each problem area (lowest dollar-per-gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to resolve the highest-priority problem areas

Projects were selected for each of the watershed-wide alternatives based on the five individual technology-specific modeling results (Conveyance, Storage, and Low GI, Medium GI, and High GI implementation). A new model including the selected projects was run for each alternative. Results for the watershed-wide model runs are presented in section 5.4.4 and 5.4.5.

FIGURE 5-2
Benefit/Cost Chart for High-priority Problem Areas 201 through 212
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



5.4.1 Alternative 1: Cost Efficiency

The first alternative focused on providing the best cost efficiency in each problem area. After removing projects that did not meet the minimum flood reduction threshold of 22 percent, the remaining projects were ranked by cost-per-gallon of flood reduction within each problem area in ascending order. The highest-ranked project, which was the project with the lowest cost-per-gallon of flood reduction, was selected for each problem area. Table 5-3 shows the selected project for each problem area. This alternative consisted primarily of conveyance solutions with one each GI and storage solution. Model results are summarized in Table 5-6 and presented on Figure 5-3.

The model results of this alternative show significant reduction in flooding, eliminating 79 percent of flooding in the high-priority problem areas. The conveyance and storage solutions in this alternative eliminated flooding in most of the high-priority problem areas.

TABLE 5-3
Selected Projects for Watershed-wide Alternative 1: Cost Efficiency
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit-Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
201	Conveyance	CONV-201	$1.80	12.9	1.161	63	$1.55
202	Conveyance	CONV-202	$0.35	103.6	0.210	79	$1.69
203	Conveyance	CONV-203	$0.22	212.2	0.953	100	$0.23
204	Conveyance	CONV-204	$0.37	113.9	0.084	100	$4.43
205	Conveyance	CONV-205	$0.39	107.1	0.956	70	$0.41
206	Conveyance	CONV-206	$0.24	218.4	0.102	100	$2.33
207	Conveyance	CONV-207	$0.34	126.5	0.410	100	$0.82
208	Conveyance	CONV-208	$0.30	134.9	0.121	100	$2.46
209	Conveyance	CONV-209	$0.56	95.1	0.233	100	$2.42
210	Storage	STOR-210	$0.09	336.6	0.010	100	$8.59
211	Conveyance	CONV-211	$0.13	438.2	0.128	100	$0.99
212	Conveyance	CONV-212	$0.08	508.6	0.058	100	$1.36
		Total	**$4.87**		**4.426**	**79**[a]	**$1.10**

Note:
Results presented in this table are based on separate technology based model runs (Conveyance, Storage, and Low, Med, and High GI)
[a] Existing flood volume for Problem Areas 201 through 212 is 5.60 MG.

5.4.2 Alternative 2: Benefit/Cost

The second alternative focused on providing the best benefit/cost in each problem area. After removing projects that did not meet the minimum flood reduction threshold of 22 percent, the remaining projects were ranked by benefit/cost in descending order. The highest-ranked project in each of the 12 problem areas, which was the project with the highest benefit/cost score, was selected. Table 5-4 shows the selected project for each problem area. This alternative consisted 12 conveyance projects. The only change relative to Alternative 1 is in Problem Area 210 where conveyance is implemented instead of storage in Alternative 1. Model results are summarized in Table 5-6 and presented on Figure 5-4.

Similar to Alternative 1, the conveyance solutions in this alternative eliminated most of the flooding in the high-priority problem areas where it was implemented. Similar to Alternative 1, this alternative results in a total flood volume reduction of 79 percent in the high-priority problem areas.

TABLE 5-4
Selected Projects for Watershed-wide Alternative 2: Benefit/Cost
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit-Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
201	Conveyance	CONV-201	$1.80	12.9	1.161	63	$1.55
202	Conveyance	CONV-202	$0.35	103.6	0.210	79	$1.69
203	Conveyance	CONV-203	$0.22	212.2	0.953	100	$0.23
204	Conveyance	CONV-204	$0.37	113.9	0.084	100	$4.43
205	Conveyance	CONV-205	$0.39	103.3	0.956	70	$0.41
206	Conveyance	CONV-206	$0.24	218.4	0.102	100	$2.33
207	Conveyance	CONV-207	$0.34	126.5	0.410	100	$0.82
208	Conveyance	CONV-208	$0.30	134.9	0.121	100	$2.46
209	Conveyance	CONV-209	$0.56	95.1	0.233	100	$2.42
210	Conveyance	CONV-210	$0.10	401.0	0.010	100	$9.85
211	Conveyance	CONV-211	$0.13	438.2	0.128	100	$0.99
212	Conveyance	CONV-212	$0.08	508.6	0.058	100	$1.36
		Total	**$4.89**		**4.426**	**79[a]**	**$1.10**

Note:
Results presented in this table are based on separate technology based model runs (Conveyance, Storage, and Low, Med, and High GI)
[a] Existing flood volume for Problem Areas 201 through 212 is 5.60 MG.

5.4.3 Alternative 3: Highest-priority Problems

The third alternative focused on resolving the highest-priority problems by combining multiple solutions within a problem area, with less emphasis on cost benefit or efficiency. This alternative also overrides the minimum threshold of 22 percent flood reduction because the goal is to eliminate as much flooding as possible from the highest-priority problem areas. Therefore, a conveyance or storage project that offered substantial flood reduction when combined with a project such as high GI, which offered less than 22 percent flood reduction, could eliminate flooding within a problem area. The best combination of solutions in terms of cost efficiency, benefit/cost, and overall flood reduction were compiled to attempt to resolve the worst problem areas. Because 12 projects were recommended in Alternatives 1 and 2 (one per project area), 12 projects were selected for Alternative 3 to keep all three alternatives relatively consistent in scale. A total of 12 projects were selected for Problem Areas 201 through 209 and again, this alternative consisted primarily of conveyance solutions with one storage project and two high GI projects. Table 5-5 shows the selected project(s) for each problem area. Model results are summarized in Table 5-6 and shown on Figure 5-5. This alternative results in a total flood volume reduction of 93 percent in high-priority problem areas 201 through 209, but did not address flooding in problem areas 210, 211, or 212.

TABLE 5-5
Selected Projects for Watershed-wide Alternative 3: Highest-priority Problems
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit-Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
201	Conveyance	CONV-201	$1.80	12.9	1.161	63	$1.55
201	High GI	HGI-201	$2.22	26.6	0.261	14	$8.50
202	Conveyance	CONV-202	$0.35	103.6	0.210	79	$1.69
202	High GI	HGI-202	$0.25	182.1	0.017	6	$14.94
203	Conveyance	CONV-203	$0.22	212.2	0.953	100	$0.23
204	Conveyance	CONV-204	$0.37	113.9	0.084	100	$4.43
205	Conveyance	CONV-205	$0.39	107.1	0.956	70	$0.41
205	Storage	STOR-205	$1.91	9.8	0.510	37	$3.74
206	Conveyance	CONV-206	$0.24	218.4	0.102	100	$2.33
207	Conveyance	CONV-207	$0.34	126.5	0.410	100	$0.82
208	Conveyance	CONV-208	$0.30	134.9	0.121	100	$2.46
209	Conveyance	CONV-209	$0.56	95.1	0.233	100	$2.42
		Total	**$8.95**		**5.017**	**93[a]**	**$1.78**

Notes:
Results presented in this table are based on separate technology based model runs (Conveyance, Storage, and Low, Med, and High GI)
[a] Existing flood volume for Problem Areas 201 through 209 is 5.38 MG.
GI = green infrastructure

5.4.4 Modeling Results

Table 5-6 provides a summary of the hydraulic model results for the three watershed-wide alternatives. Alternative 3 provides the greatest reduction of flooding in the system in terms of total volume and duration of flooding. Alternative 2 minimizes the total length of pipe experiencing flooding in the system overall. However, there is no significant difference in the results of all three alternatives in terms of flood reduction on a linear footage basis or total duration of flooding or surcharge. Maps comparing the model results are presented on Figures 5-3 through 5-5.

Each of the alternatives analyzed still leaves areas with flooding (as shown by red lines on the maps), largely because those areas are outside the boundaries of the high-priority problem areas. These areas were not addressed by solutions because they were either flooding at isolated structures, or did not score high based on the problem identification scoring criteria.

TABLE 5-6
Summary of Watershed-wide Alternative Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Existing Condition Results				Alternative 1 Best Cost Efficiency				Alternative 2 Best Benefit/Cost Ratio				Alternative 3 Highest-priority Problems			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	21,836	38	-	-	30,908	53	-	-	30,715	53	-	-	30,667	53	-	-
Surcharged[a]	10,399	18	346	-	8,435	14	234	-	8,605	15	236	-	8,320	14	236	-
Insufficient Freeboard	10,107	17	-	-	7,844	13	-	-	8,112	14	-	-	7,776	13	-	-
Flooded	15,965	27	131	1,391,774	11,122	19	82	920,344	10,877	19	82	926,470	11,556	20	80	852,901

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

FIGURE 5-3
Alternative 1: Cost-efficiency Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

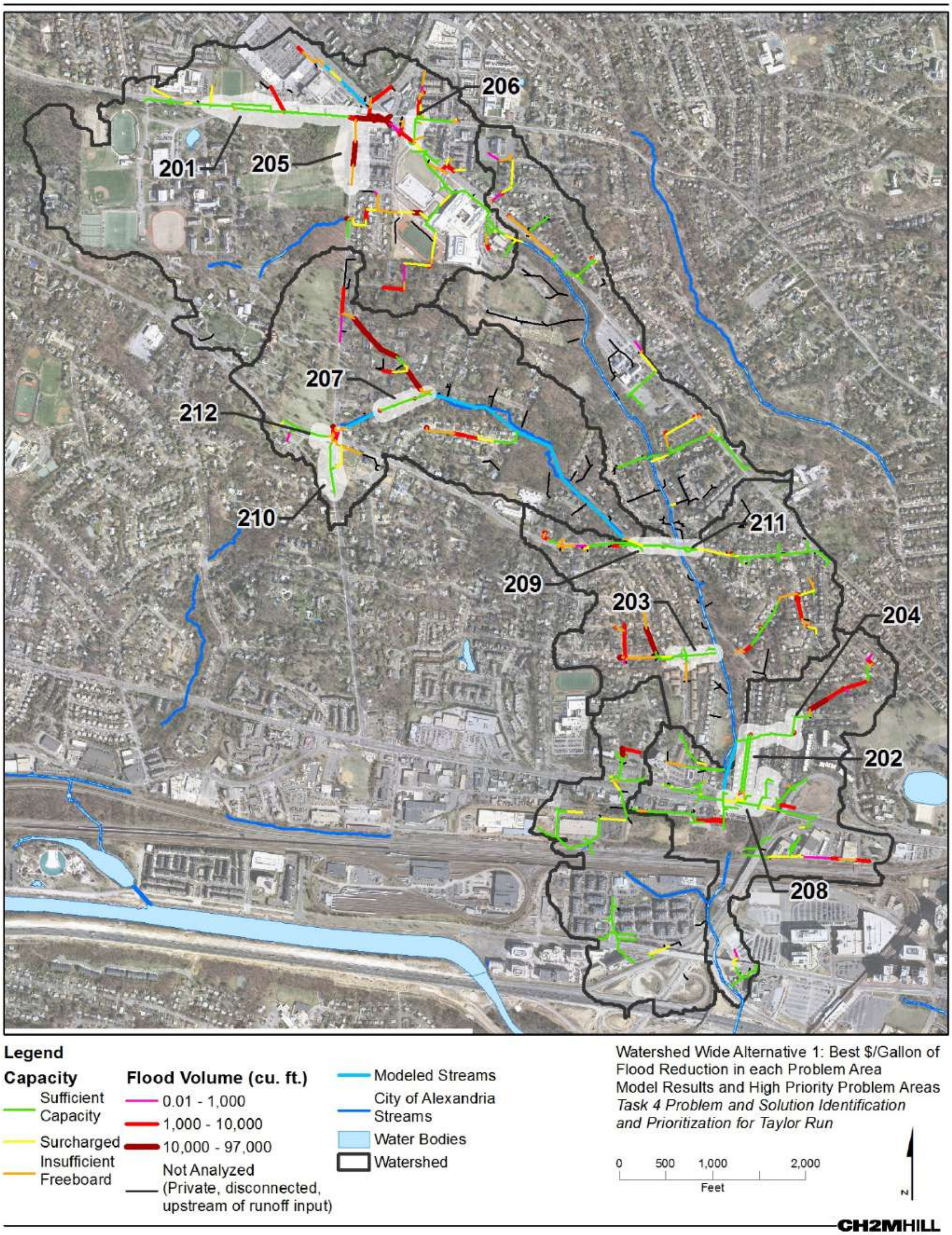


FIGURE 5-4
Alternative 2: Benefit/Cost Model Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

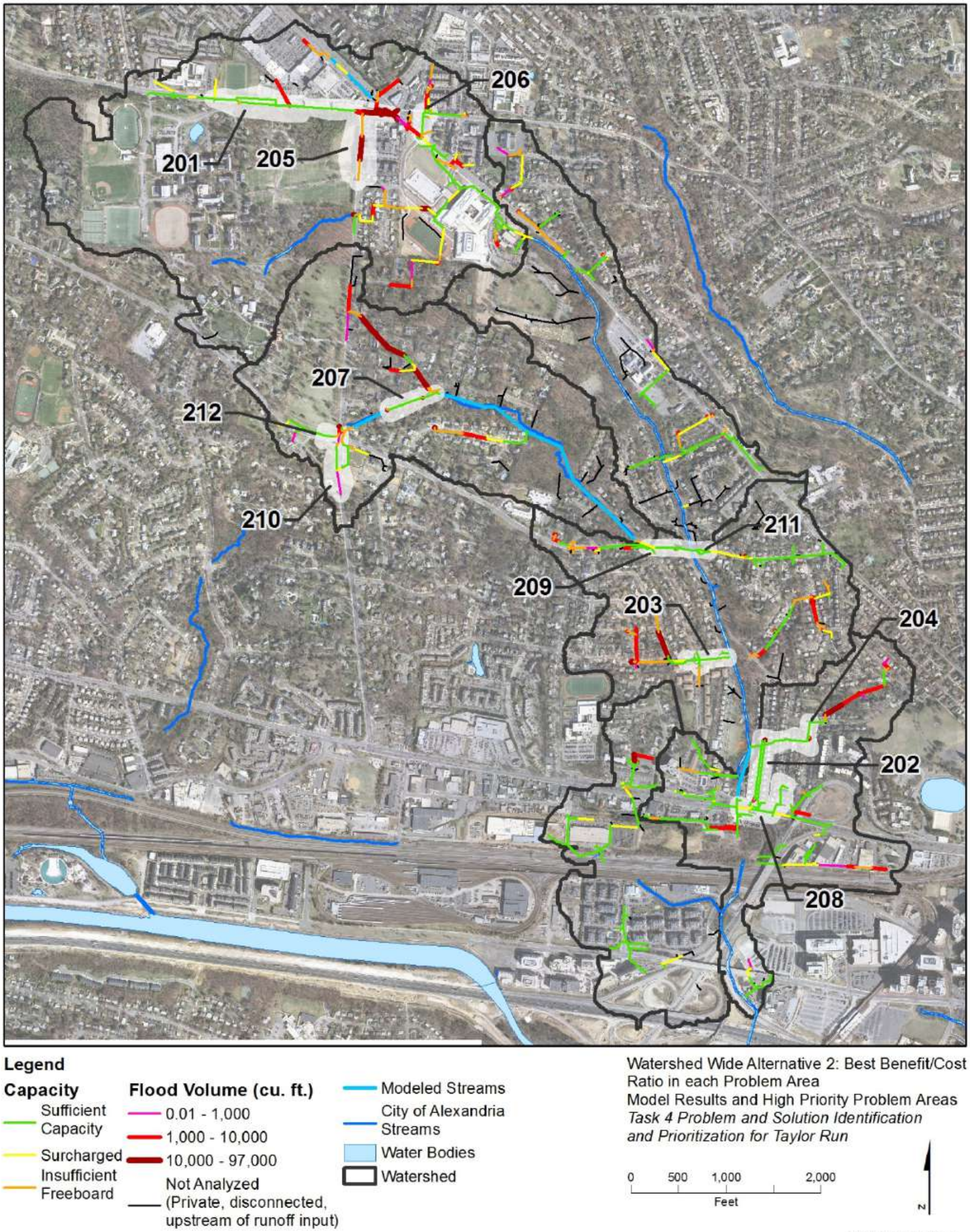


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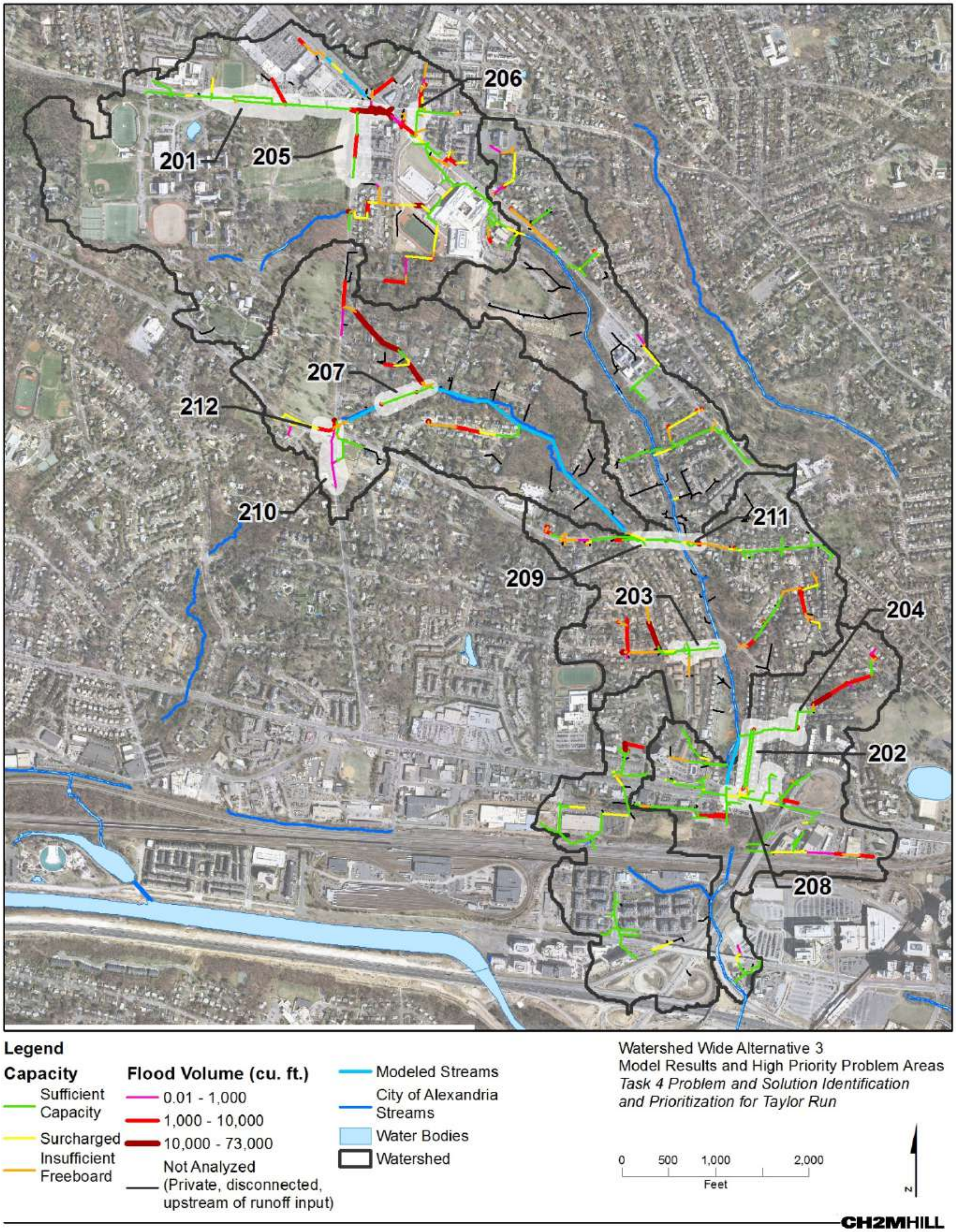
FIGURE 5-5
Alternative 3: Highest-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



5.4.5 Scoring and Prioritization Results

The results for each alternative generally reflect the objective of that particular alternative. A summary of the results is provided in Table 5-7 below. A model was run for each of the alternatives, so the alternative-specific results presented in Table 5-7 may differ slightly from the results generated from the technology-specific model runs used to evaluate each solution type.

Alternative 1 and Alternative 2 provide, comparably, the lower cost and cost per gallon of flood reduction, but Alternative 2 provides the highest benefit and benefit/cost scores. Although Alternative 3 provides the highest total volume of flood reduction, it also has the highest cost per gallon of flood reduction and lowest overall benefit/cost ratio. Therefore, Alternative 2 is the most beneficial and cost effective watershed-wide alternative even though there is not a significant difference between Alternative 2 and Alternative 1 in terms of cost.

TABLE 5-7
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run

	Alternative 1 - Best Cost Efficiency	Alternative 2 - Best Benefit/Cost Ratio	Alternative 3 – Highest-priority Problems
Total Cost ($ Millions)	$4.87	$4.89	$7.36
Total Benefit Score	501	516	538
Overall Benefit/Cost	103	106	73
Total Flood Reduction (MG)	4.47	4.43	4.66
$/Gallon of Flood Reduction	$1.10	$1.10	$1.58

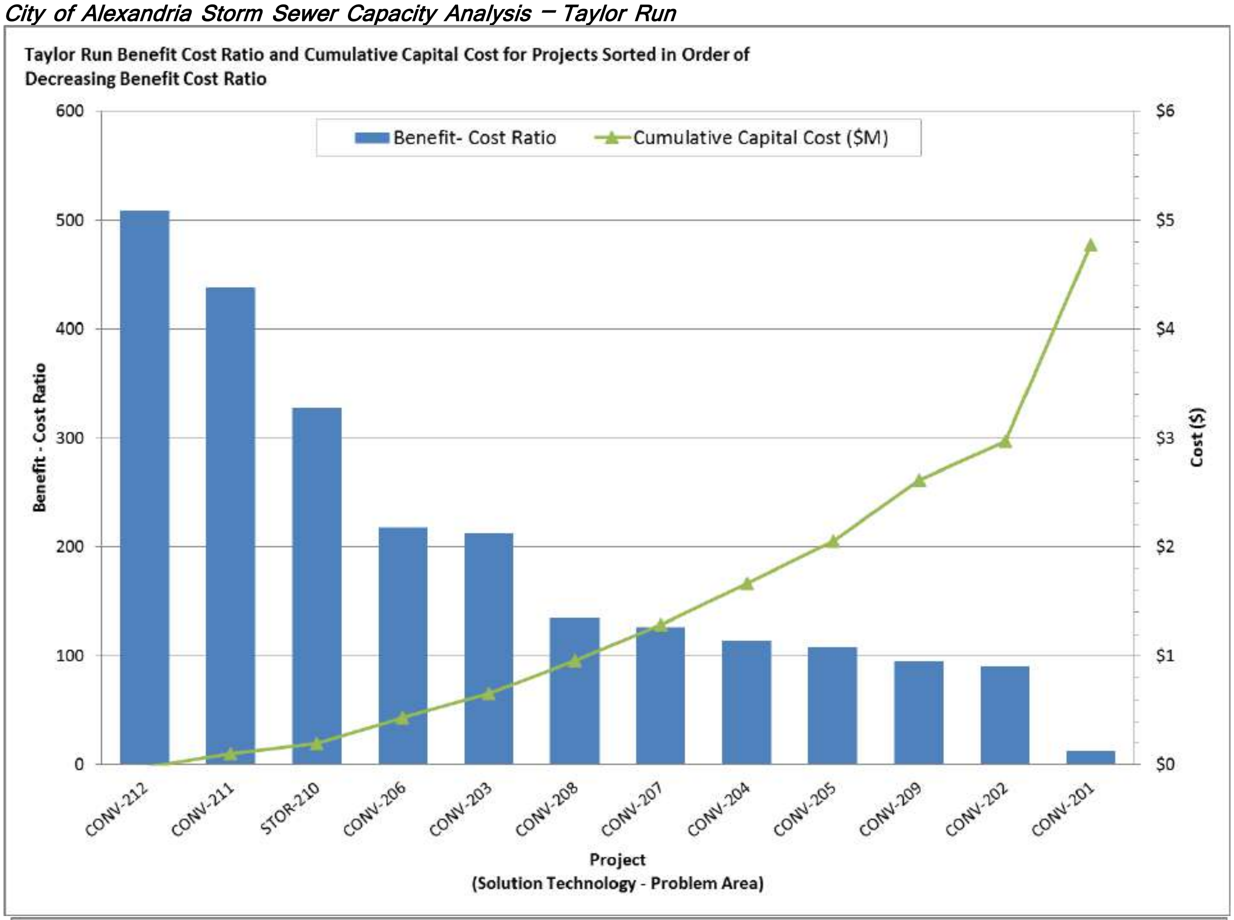
Note:
Results presented in this table are based on watershed-wide alternative models that include the selected projects documented in sections 5.4.1-5.4.3.

When developing a capital improvement plan, the benefit cost or cost efficiency ($/gallon of flood reduction) are typically used to guide the order in which projects are implemented. Prioritization results for the three watershed-wide alternatives are presented in Figures 5-6 through 5-8. The top chart shows the benefit cost ratio and the cumulative capital cost of the alternative. The solutions are provided in order of decreasing benefit cost ratio; solutions with the greatest benefit cost ratio are presented on the left and solutions with the lowest benefit cost ratio are presented on the right.

The bottom chart shows the benefit/cost ratio for each solution in the watershed-wide alternative in order of increasing cost/gallon of flood reduction. In watershed-wide Alternative 1 and Alternative 2, the best cost efficiency and best benefit/cost ratio alternatives, there is one low level green infrastructure solution that has no value for the cost/gallon of flood reduction. This solution, shown on left side of the chart, is in problem area 204 that experience an increase in flooding after implementing the selected solutions for the watershed-wide alternative. In both alternatives the selection of a conveyance solution upstream and/or downstream of this problem areas increases peak flow upstream and backwater downstream of this problem area, which contributes to an increase in flooding elsewhere in the system.

Both charts show the cumulative capital cost plotted on the secondary axis. The solutions on both charts are named by the technology: conveyance (CONV), storage (STOR), low green infrastructure (LGI), medium GI (MGI), or high GI (HGI), and the problem area number.

FIGURE 5-6
Alternative 1: Best Cost Efficiency Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



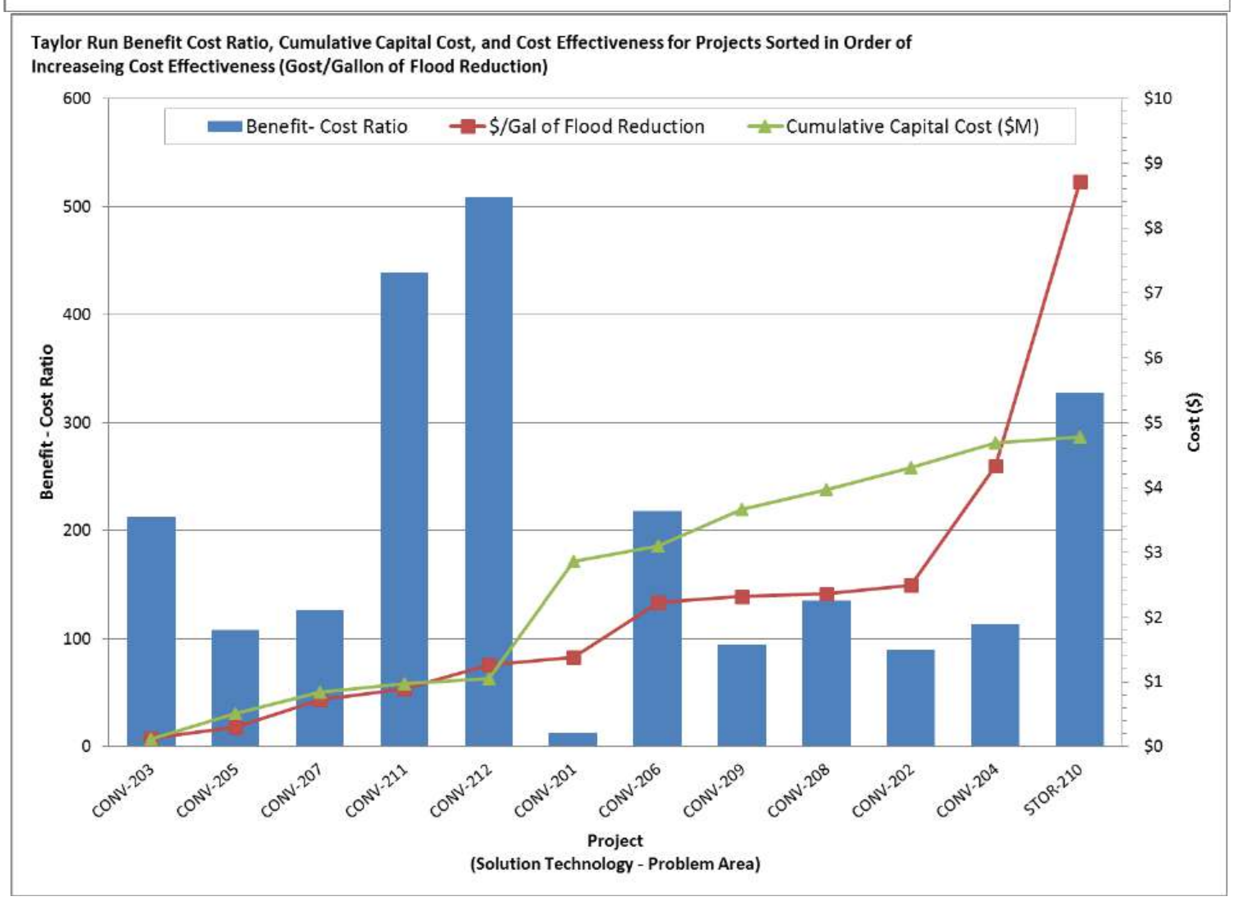
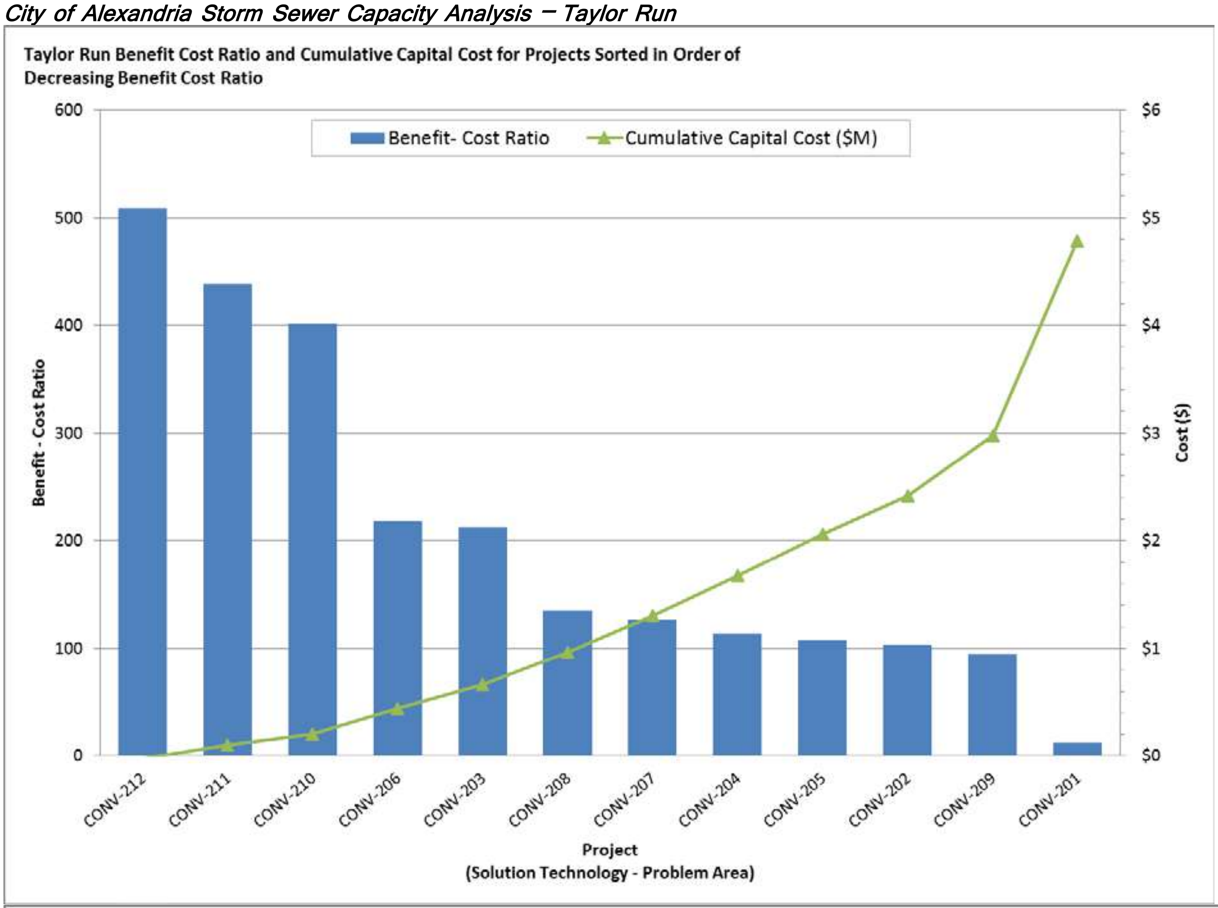


FIGURE 5-7
Alternative 2: Best Benefit/Cost Ratio Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



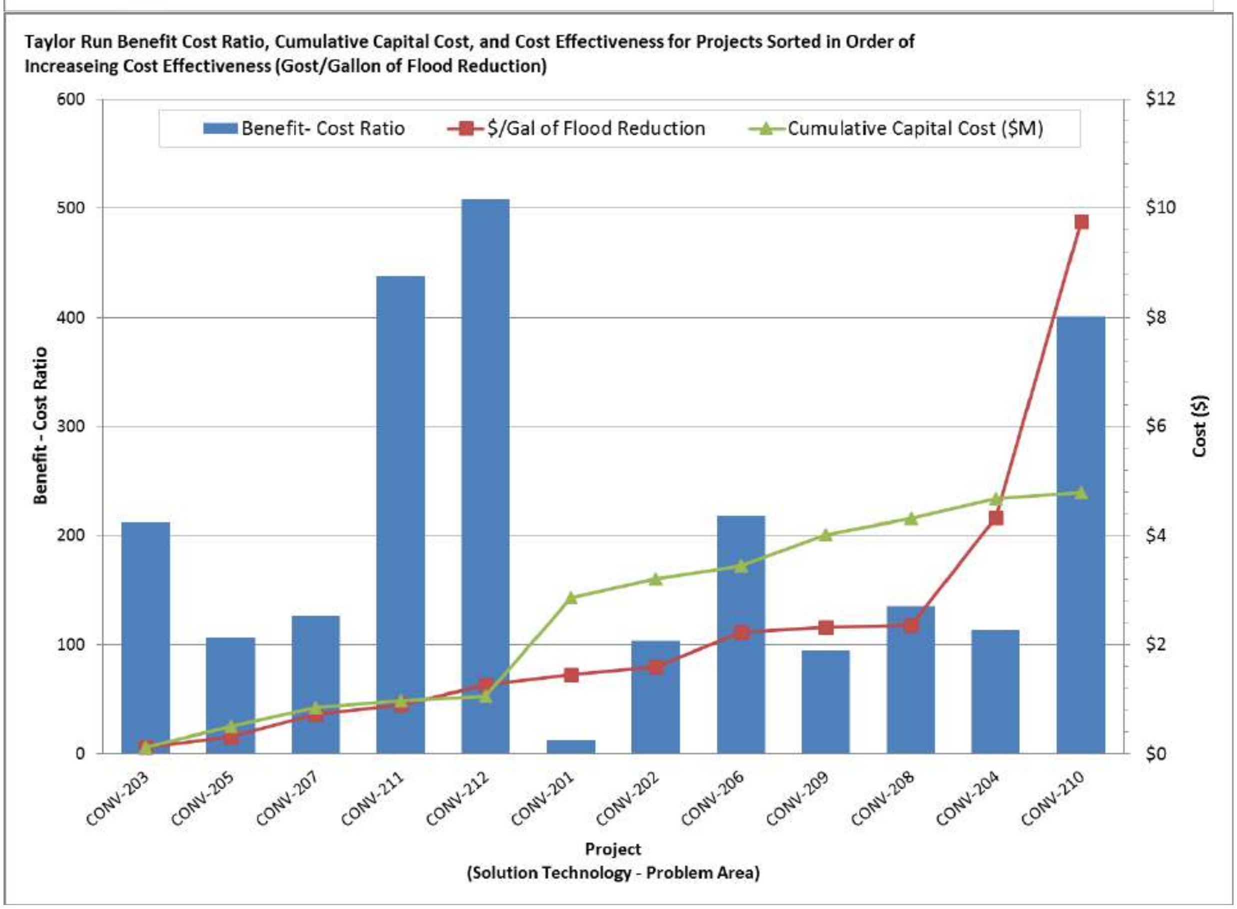
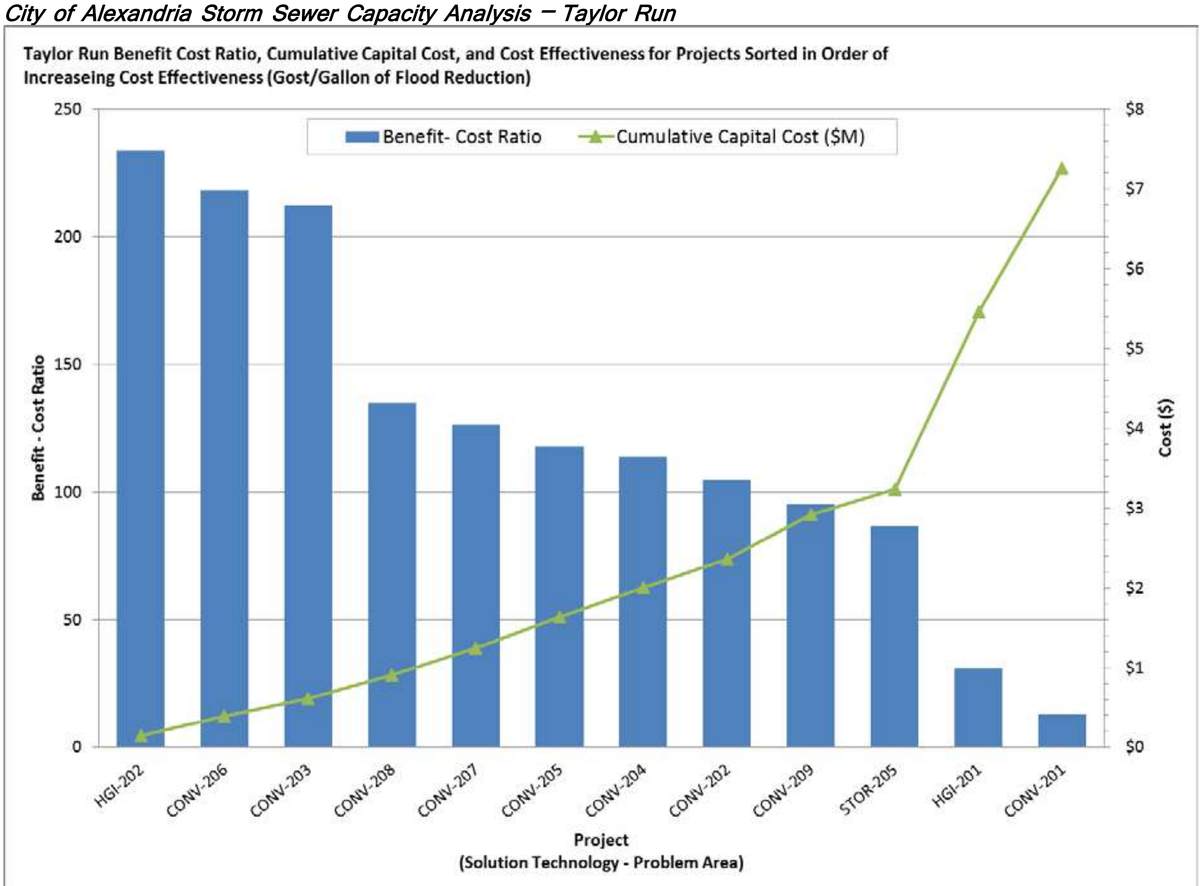
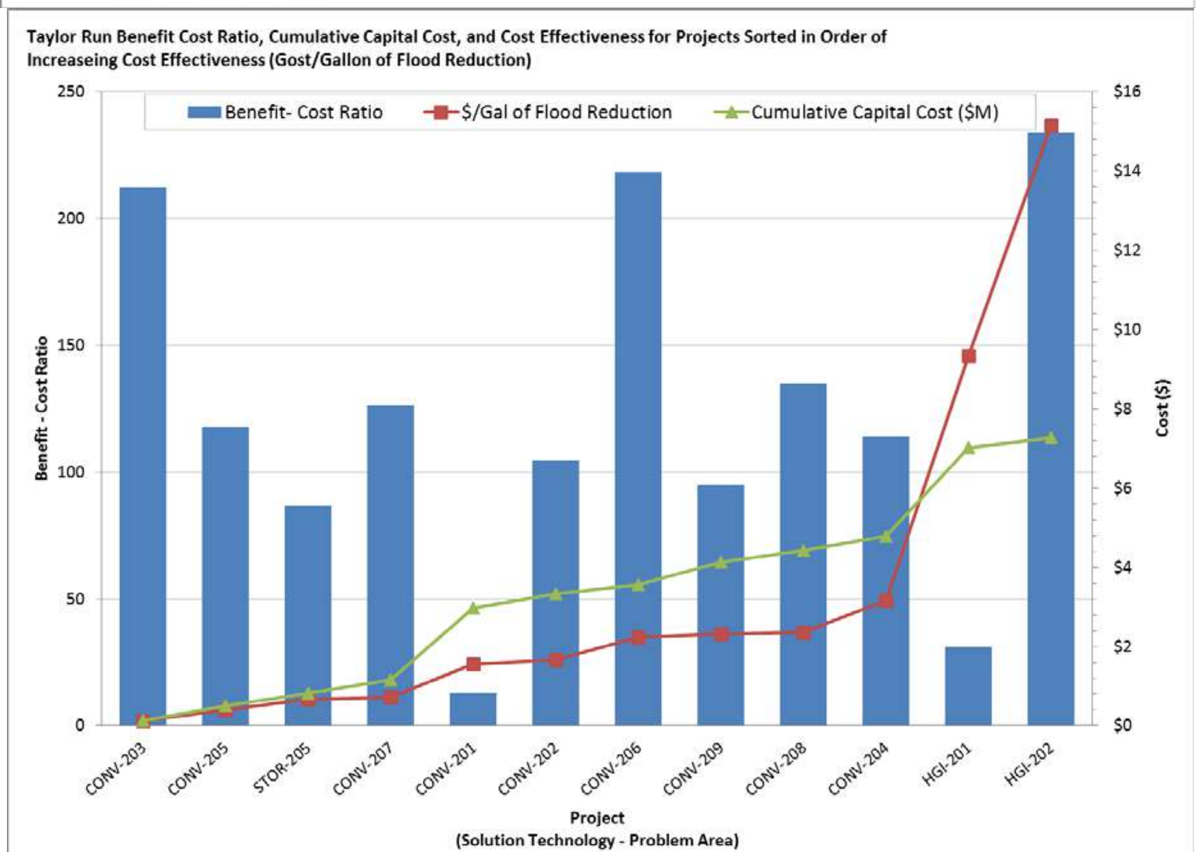


FIGURE 5-8
Alternative 3: Highest-priority Problems Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run





SECTION 6

Summary

The objectives of this phase of the study were to 1) identify and prioritize capacity problems based on modeling results from Task 2 of this project, and 2) develop and prioritize solutions to address those problems. The first objective was accomplished in two steps. The first step included evaluating each stormwater junction in the drainage network using a scoring system to identify problems based on several criteria, including the severity of flooding, proximity to critical infrastructure and roadways, identification of problems by city staff and the public, and opportunity for overland relief. In the next step of this objective, high-scoring junctions (that is, higher-priority problems) were grouped together to form high-priority problem areas. In total, 12 high-priority problem areas were identified in the Taylor Run watershed.

The second objective involved developing and prioritizing solutions to address capacity limitations within the 12 high-priority problem areas. To accomplish this objective, several strategies involving different technologies were examined, including improving conveyance by increasing hydraulic capacity, reducing capacity limitations by adding distributed storage to the system, and reducing stormwater inflows by implementing green infrastructure (GI). Each of these strategies required a different modeling approach. Conveyance improvements were modeled by increasing pipe diameter in key locations within the problem area, storage was added as storage nodes based on a preliminary siting exercise, and GI was modeled as a reduction in impervious area at three different implementation levels: high, medium, and low. A single model run was set up and run for each strategy addressing all 12 high-priority problem areas and the results were compiled for the alternatives and prioritization evaluation. Solutions were evaluated based on several criteria, including drainage improvement/flood reduction, environmental compliance, sustainability and social benefits, asset management and maintenance implications, constructability, and public acceptance. Planning-level capital costs were developed for each solution to facilitate a benefit cost analysis and prioritization process.

The results of the solution identification and prioritization analysis show the following results for Taylor Run:

- In terms of solution technology performance:
  - Conveyance solutions generally have the greatest overall benefit.
  - Conveyance and storage solutions generally provide the greatest flood reduction of the technologies/approaches analyzed.
- In terms of costs:
  - A low level of GI implementation generally has the greatest benefit/cost score, but did not usually meet the minimum threshold for flood reduction.
  - Conveyance projects generally provide the most economical stormwater volume reduction in terms of dollars per gallon of flood reduction within a high-priority problem area.

Three watershed-wide alternatives were developed, including:

- Alternative 1: Most cost-effective solution for each problem area (lowest dollar-per-gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to resolve the worst problem areas

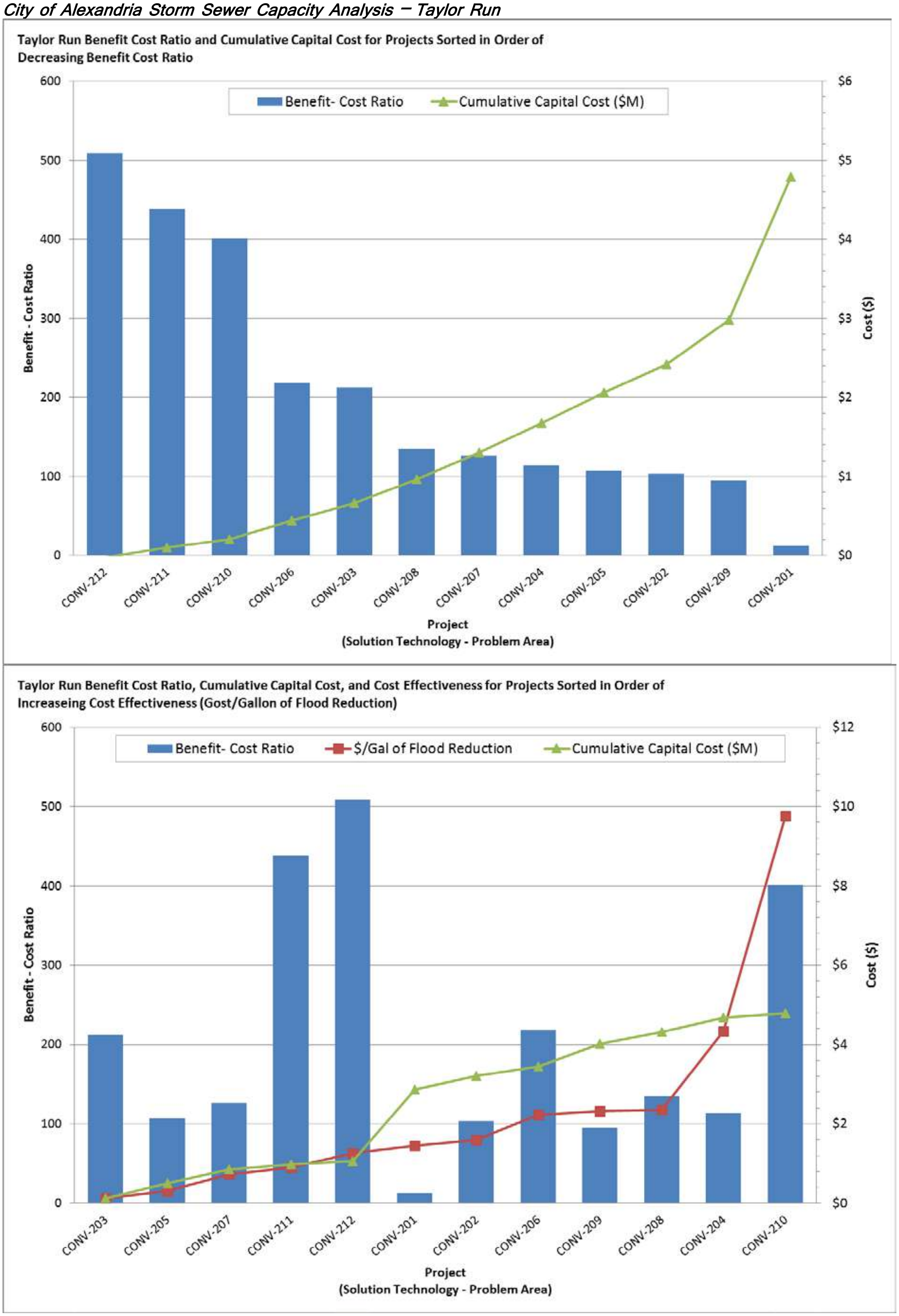
Conveyance projects dominate the list of solutions for all three watershed-wide alternatives in Taylor Run. This is because the Taylor Run storm sewer system is made up of smaller systems that discharge into the Taylor Run stream, which runs from north to south. Many of the capacity issues affect a few pipes at the downstream end of these smaller systems near the outlet to the stream, and do not occur far upstream. As such, conveyance improvements increase capacity, eliminating flooding in these localized areas, and because there are no downstream collection systems, there are no adverse effects. Because impacts to the stream channel are not being explicitly evaluated, if a project increases the peak flow to the stream channel this is not accounted for.

Because of the dominance of conveyance projects, Alternative 1 and Alternative 2 only differ in one of the 12 problem areas. Problem Area 210 where storage is the highest ranked solution for cost efficiency and conveyance is the highest ranked solution for benefit cost. Alternative 1 and Alternative 2 provide similar amounts of flood reduction for essentially the same total cost and cost per gallon of flood reduction but Alternative 2 has marginally higher benefit and benefit/cost scores. Alternative 3 provides the highest total volume of flood reduction, but it also has the highest cost per gallon of flood reduction and lowest benefit and benefit/cost scores. Therefore, Alternative 2 is the most beneficial and cost effective watershed-wide alternative. Two suggested prioritization of watershed-wide Alternative 2 projects are provided in Figure 6-1; projects can be prioritized either based on overall benefit/cost ratio or cost efficiency (cost per gallon of flood reduction).

It should be noted that the model does not include analysis on private property, but applies assumed runoff loads as inputs to the public conveyance system. The City chose not to include existing private or most public stormwater management facilities (e.g., detention and retention ponds) upstream of the modeled collection system because of the limited available information on these facilities and a concern that the facilities may not be performing as designed. When the City moves forward into detailed evaluation and design of selected projects, it will be important to fully evaluate and account for the benefits of any existing stormwater management facilities.

The hydraulic modeling results and costs presented in this report should be reviewed with the understanding that several assumptions were made to fill data gaps in the hydraulic model, and proposed solutions and costs were developed on a planning level.

FIGURE 6-1
Alternative 2: Best Benefit/Cost Ratio Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Taylor Run



SECTION 7

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Appendix A
Conveyance Solutions

Appendix A - Conveyance Solutions

Summary of Conveyance Solutions Developed for Taylor Run High-Priority Problem Areas

Problem Area	FacilityID	Upstream Node Name	Downstream Node Name	Length ft	Proposed Shape	Existing Diameter/ Height (ft) x Width (ft)	Proposed Diameter/ Height (ft) x Width (ft)	Conduit Slope	Number of Barrels	Roughness
201	000022STMP	000048SMH	000037SMH	125.947	Circular	3.5	6.5	0.699	1	0.013
201	000036STMP	000037SMH	000005SMH	114.037	Circular	3.5	6.5	0.859	1	0.013
201	000038STMP	000003SMH	000048SMH	71.549	Circular	3.5	6	1.286	1	0.013
201	000039STMP	000041SMH	000003SMH	72.696	Circular	3.5	6	1.609	1	0.013
201	000040STMP	000042SMH	000041SMH	128.008	Circular	3.5	6	1.531	1	0.013
201	000041STMP	000004SMH	000042SMH	127.678	Circular	3.5	5.5	2.036	1	0.013
201	000042STMP	000043SMH	000004SMH	295	Circular	3.5	5.5	1.878	1	0.013
201	000044STMP	000044SMH	000043SMH	149.846	Circular	3	5.5	1.815	1	0.013
201	000047STMP	000045SMH	000044SMH	147.056	Circular	3	5.5	1.659	1	0.013
201	000049STMP	000046SMH	000045SMH	378.347	Circular	3	5.5	1.829	1	0.013
201	000052STMP	000029IN	000047SMH	61.669	Circular	1	1.5	1.388	1	0.013
201	000053STMP	000032IN	000031IN	7.595	Circular	1	2	1.383	1	0.013
201	000054STMP	000031IN	000030IN	8.496	Circular	1	2	1.389	1	0.013
201	000055STMP	000030IN	000029IN	7.445	Circular	1	2	1.397	1	0.013
201	005779STMP	003769IN	000032IN	316.94	Circular	1.25	2	1.389	1	0.013
201	005783STMP	001203SMH	000046SMH	44.331	Circular	1.75	2.5	3.596	1	0.013
201	005785STMP	001202SMH	001203SMH	229.075	Circular	1.75	2.5	4.978	1	0.013
202	000497STMP	000018CB	000618IN	615.562	Circular	1	2	1.886	1	0.013
202	000498STMP	000612IN	000018CB	7.287	Circular	1	1.5	3.705	1	0.013
202	000500STMP	000614IN	000225SMH	20.097	Circular	1	2	3.249	1	0.013
202	000501STMP	000615IN	000614IN	8.398	Circular	1	1.5	3.251	1	0.013
202	000502STMP	000616IN	000615IN	7.832	Circular	1	1.5	3.243	1	0.013
202	000504STMP	000617IN	000621IN	88.221	Circular	1.25	2	1.017	1	0.013
202	000667STMP	000618IN	000617IN	10.813	Circular	1	2	1.887	1	0.013
202	000668STMP	000019CB	000614IN	618.845	Circular	1	1.5	1.258	1	0.013
202	000671STMP	000621IN	000622IN	75.901	Circular	1.25	2.5	0.723	1	0.013
202	000672STMP	000622IN	000237SMH	39.297	Circular	1.5	2	3.794	1	0.013
203	001639B	000087ND	000041IO	65.82	Circular	1.5	2.5	3.801	1	0.013
203	000358STMP	000207SMH	000208SMH	18.515	Circular	1.5	4	0.486	1	0.013
203	000359STMP	000208SMH	000209SMH	18.46	Circular	1.5	3.5	3.846	1	0.013
203	000360STMP	000512IN	000208SMH	30.096	Circular	1.5	2	3.645	1	0.013
203	001637STMP	000515IN	000512IN	46.41	Circular	1.5	2.5	2.43	1	0.013
203	001639A	000209SMH	000087ND	233.246	Circular	1.5	3	3.803	1	0.013
203	001683STMP	000595IN	000206SMH	11.579	Circular	1.5	2	6.477	1	0.013
203	001684STMP	000206SMH	000207SMH	115.311	Circular	1.5	3	5.975	1	0.013
204	001700STMP	000256SMH	000687IN	25.316	Circular	2	4	1.738	1	0.013
204	014562STMP	000687IN	002099ND	108.235	Circular	2	3.5	3.865	1	0.013

Appendix A - Conveyance Solutions

Summary of Conveyance Solutions Developed for Taylor Run High-Priority Problem Areas

Problem Area	FacilityID	Upstream Node Name	Downstream Node Name	Length ft	Proposed Shape	Existing Diameter/ Height (ft) x Width (ft)	Proposed Diameter/ Height (ft) x Width (ft)	Conduit Slope	Number of Barrels	Roughness
204	014520STMP	000233SMH	000101ND	163.916	Circular	2	5	0.193	1	0.013
204	014519STMP	000101ND	000231SMH	43.902	Circular	2	2.5	8.708	1	0.013
204	014518STMP	000231SMH	000097ND	184.531	Circular	2	3.5	2.186	1	0.013
204	014517STMP	000097ND	000227SMH	26.633	Circular	2	2.5	13.277	1	0.013
204	014516STMP	000227SMH	000098ND	25.194	Circular	2	3.5	2.485	1	0.013
204	014515STMP	000098ND	000256SMH	108.895	Circular	2	3.5	2.483	1	0.013
205	000009STMP	000074IN	000073IN	249.031	Circular	1.5	3	1.095	1	0.013
205	000010STMP	000075IN	000074IN	214.771	Circular	1.5	3	1.045	1	0.013
205	000076STMP	000073IN	000007SMH	242.137	Circular	1.75	4	1.834	1	0.013
205	000078STMP	000027IN	000003SMH	11.798	Circular	2	4.5	-1.178	1	0.013
205	000080STMP	000007SMH	000027IN	8.761	Circular	2	3	7.294	1	0.013
206	008621A	002578SMH	000692ND	42.189	Circular	1.5	3	1.083	1	0.013
206	008613STMP	005536IN	005537IN	9.09	Circular	1	1.5	1.045	1	0.013
206	008614STMP	005537IN	002578SMH	59.376	Circular	1	1.5	1.043	1	0.013
206	008621B	000692ND	002579SMH	182.374	Circular	1.5	3	1.085	1	0.013
206	008622STMP	002573SMH	002578SMH	28.418	Circular	1.25	2	3.857	1	0.013
206	014532STMP	002579SMH	000050SMH	34.042	Circular	1.5	2	11.574	1	0.013
207	000404STMP	000085SMH	000121ND	148.507	Circular	2	4	3.375	1	0.013
207	001397STMP	000097SMH	000086SMH	334.461	Circular	2	4	3.16	1	0.013
207	001398STMP	000086SMH	000085SMH	27.216	Circular	2	4	2.462	1	0.013
207	014524STMP	000098SMH	000060ND	8.172	Circular	2	4	3.157	1	0.013
207	014523STMP	000060ND	000097SMH	28.074	Circular	2	4	3.16	1	0.013
208	000362STMP	000022CB	000228SMH	46.483	Circular	1	1.5	5.86	1	0.013
208	000426STMP	000237SMH	000008ND	132.137	Circular	2.5	4	1.389	1	0.013
208	000427STMP	000238SMH	000237SMH	250.716	Circular	2.5	3.5	1.922	1	0.013
208	000429STMP	000229SMH	000631IN	44.657	Circular	1.25	2	3.153	1	0.013
208	000560STMP	000228SMH	000229SMH	159.822	Circular	1	1.5	3.524	1	0.013
208	000564STMP	000631IN	000238SMH	96.343	Circular	1.5	2	2.783	1	0.013
209	001062B	000111ND	000056IO	134.046	Circular	5	7.5	1.736	1	0.013
209	001062A	000291SMH	000111ND	253.16	Circular	5	7.5	1.629	1	0.013
209	014514STMP	000297SMH	000116ND	51.248	Circular	2	2.5	7.893	1	0.013
209	014513STMP	000116ND	000291SMH	30.346	Circular	2	3.5	1.664	1	0.013
210	002411STMP	001292IN	000890IN	250.719	Circular	1.25	2	3.409	1	0.013
210	014970STMP	000890IN	009919IN	62.442	Circular	1	2.5	1.601	1	0.013
211	001737A	000284SMH	000109ND	25.801	Circular	2	3.5	2.399	1	0.013
211	001733STMP	000753IN	000283SMH	32.095	Circular	1.75	4.5	-0.041	1	0.013
211	001736STMP	000283SMH	000284SMH	122.68	Circular	2	3	7.284	1	0.013

Appendix A - Conveyance Solutions

Summary of Conveyance Solutions Developed for Taylor Run High-Priority Problem Areas

Problem Area	FacilityID	Upstream Node Name	Downstream Node Name	Length ft	Proposed Shape	Existing Diameter/ Height (ft) x Width (ft)	Proposed Diameter/ Height (ft) x Width (ft)	Conduit Slope	Number of Barrels	Roughness
211	001737B	000109ND	000055IO	40.283	Circular	2	3.5	2.396	1	0.013
212	001782STMP	000879IN	000309SMH	26.039	Circular	2	3.5	0.307	1	0.013
212	001783STMP	000880IN	000879IN	54.457	Circular	1.75	2.5	2.384	1	0.013
212	001784STMP	000881IN	000880IN	103.967	Circular	1.75	2.5	1.873	1	0.013

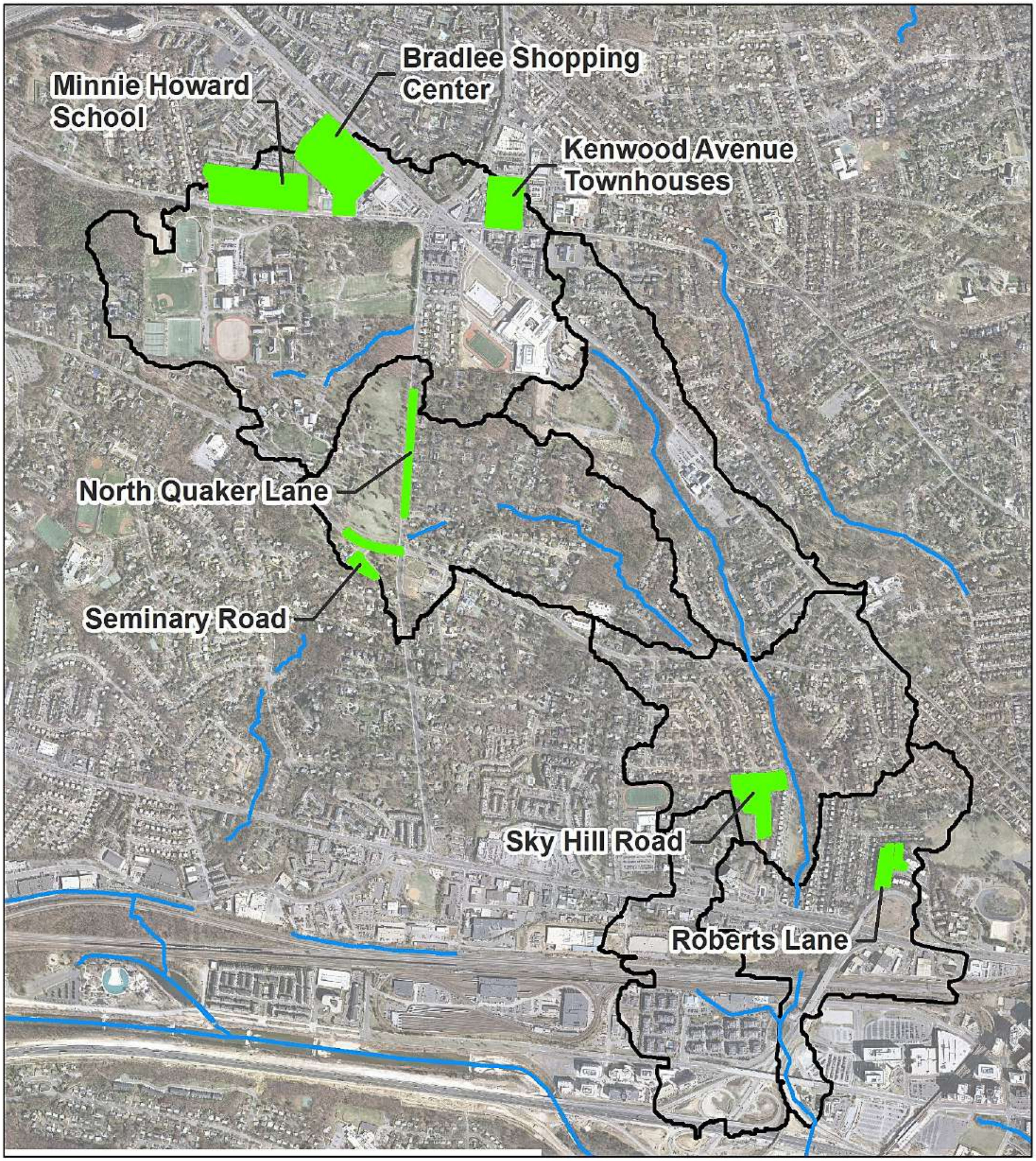
Appendix B
Storage Solutions

Appendix B - Storage Solutions

Summary of Storage Solutions Developed for Taylor Run High-Priority Problem Areas

Problem Area	Storage ID	Overflow Node	Discharge Node	Storage Area (ac)	Storage Area (ft^2)	Overflow Weir Crest (ft)	Overflow Weir Crown (ft)	Storage Invert Elevation (ft)	Storage Rim Elevation (ft)	Storage Depth (ft)	Storage Volume (ft^3)	Notes
201	12	001202SMH	000044SMH	0.04	1,845	225.22	231.00	208.00	218	10.00	18,448	
203	4	000518IN	000209SMH	0.03	1,200	84.99	89.00	76.00	86	9.59	11,503	
205	13	000075IN	000007SMH	0.31	13,696	198.78	202.00	190.00	200	9.38	128,493	
206	11a	002593SMH	002578SMH	0.08	3,530	192.69	199.00	188.00	198	5.07	17,880	
206	11b	002549SMH	000692ND	0.01	403	193.48	198.00	184.08	194.08	10.00	4,031	
208	1	000239SMH	000237SMH	0.10	4,289	49.41	59.00	44.00	54	6.41	27,495	
209	5	000294SMH	000292SMH	0.01	348	103.91	108.00	96.00	106	8.71	3,027	
210	8	000890IN	000310SMH	0.01	413	212.54	215.00	200.76	210	10.00	4,131	
212	9	000881IN	000309SMH	0.06	2,407	205.79	210.00	200.07	206.315	6.25	15,030	

Appendix C
Green Infrastructure Concept Plans



LEGEND

City of Alexandria Streams

Concept Plan Locations

Subwatersheds

Task 4 Green Infrastructure Program Concepts for Taylor Run

Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

0 750 1,500 3,000 Feet

N

Potential Sites for Task 4 Concept Development in Taylor Run

PREPARED FOR: City of Alexandria TE&S Department

COPY TO: File

PREPARED BY: CH2M HILL

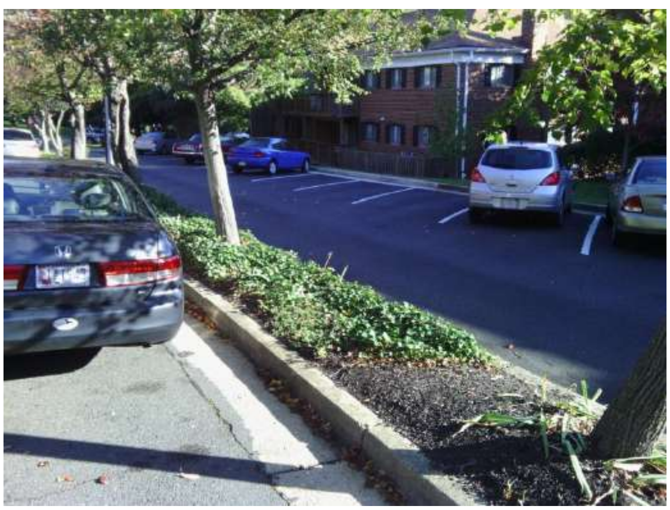
DATE: February 12, 2016

PROJECT NUMBER: 240027

The following is documentation of the sites identified as potential locations for green infrastructure (GI) concept development in Taylor Run. For each site a program and the elements of the program are identified with field notes as well as pros and cons of GI implementation. Sites are described with the southernmost site in Taylor Run first, moving north into the watershed. A map of the watershed and all potential sites, as well as a detailed map of each individual site, is also provided in Appendix C for reference.

Sky Hill Road

Street/Side Street Parking



Northeast of Dartmouth Rd & Sky Hill Rd. Downstream of Parking and Street

Program Type: Green Buildings, Green Parking

GI Concepts: Planters/Bioretention, Porous Pavement

Field Notes:

- Planters can be placed along sidewalk adjacent to buildings to capture runoff from roof drains
- Significant parking area for apartment tenants is an opportunity for porous pavement
- Parking and street slope to the northeast at Dartmouth Rd and Sky Hill Rd, a location suitable for bioretention. Bioretention can be placed in grassy area on northeast side of parking lot and street at Dartmouth Rd and Sky Hill Rd to capture runoff from roadway

Pros:

- Large stormwater capture potential
- Slope of lot makes capture easy at downstream end of street and parking lots
- Parking areas are typically easier and more cost effective to implement
- Good infiltration potential.
- Could alleviate severe downstream capacity limitations.
-

Cons:

- Requires coordination with private property owners

Roberts Lane

Apartment Street/Parking

North of Property for Bioswale/Bioretention combination

Steep Slope Behind Apartment Bldg.

Potential Bioretention Area at the end of Robert's Lane

Program Type: Green Parking, Green Buildings

GI Concepts: Soil amendment and a combination of bioswale and bioretention would improve infiltration and prevent erosion of the steep slopes at this location.

Planters placed adjacent to the building could be used to capture roof runoff which currently connects to the storm system.

Porous Pavement (parking lot), potential for rainwater harvesting and reuse for irrigation

Field Notes:

- A combination of steep and gentle slope at this location presents opportunities for open space concept to include bioswale, bioretention, and soil amendment.
- There is rock-lined ditch at the north of the site that could be converted to a bioswale to aid infiltration.
- Large parking spaces are potential for porous pavement application

Pros:

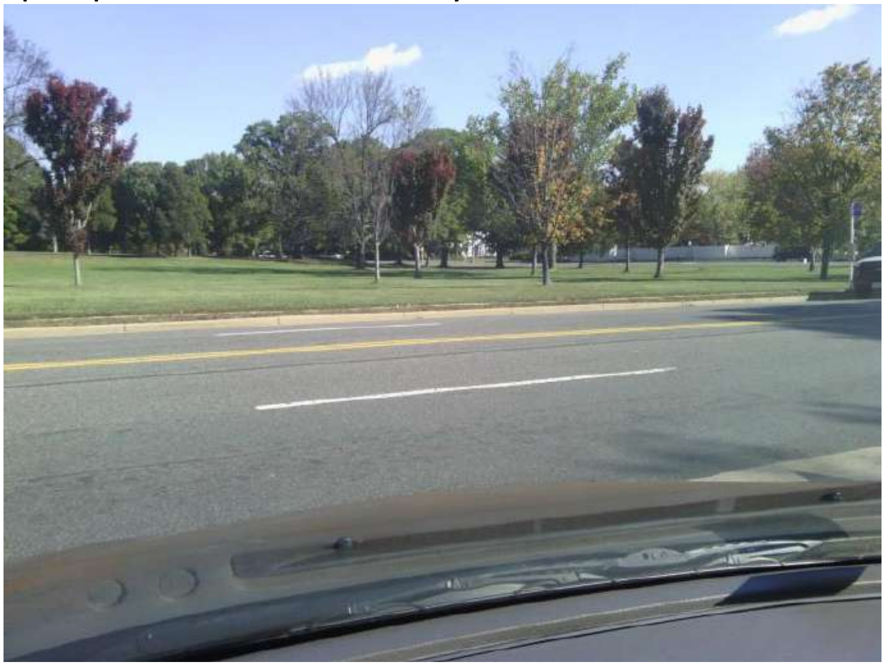
- Large impervious parking surface with gentle slope to a central location at the north
- Pervious space available for low impact low cost soil amendment application
- Potential to relieve downstream capacity deficient sewers

Cons:

- Steep slopes may not be conducive to some GI technology applications.
- Requires coordination with private property owners

Seminary Road

Opens Space on the NE Quad of Seminary Road at North Quaker Lane



Program Type: Green Street/ Green Parking

GI Concepts: Detention (storage), Bioretention/ Amended Soils

Field Notes:

- Large open area at the northeast quadrant of Seminary Rd and N Quaker La intersection has the potential for detention/storage
- Bioretention opportunity near the church parking lot and driveway and amended soils application at the edges of the parking lot on south side of Seminary Road
- Most of the parking lot at the Church on the SW quadrant of the intersection drains through pervious surfaces and did not provide significant opportunities for GI application
- Roof drainage from the church is disconnected to depressed area next to the building

Pros:

- Large open space
- Runoff redirection to detention has the potential to relieve downstream sewer capacity deficiency
- Parking areas typically are simpler construction and more cost-effective to implement

Cons:

- Private property
- Limited opportunity for GI application on parking lot

North Quaker Lane

N Quaker Lane – Looking north from Seminary Road

N Quaker Lane – Looking north from Aspinwall Lane

Source: Google Maps Street View ™

Program Type: Green Street

GI Concepts: Bioretention, and Planter

Field Notes:

- Wide road with opportunity for bioretention and planters
- Space for storage
- Large green space allows for adjustment in sidewalk to create space for bioretention or bioswale

Pros:

- Wide road with room to operate
- Porous pavement on sidewalk provides aesthetic value and appealing to residents
- Public right of way
- Could provide relief to pipes with deficient capacity downstream

Cons:

- Road was recently paved. No apparent opportunity to piggy back an existing CIP.

Minnie Howard School

East Entrance/Parking

West Entrance/Parking

Source: Google Maps Street View ™

Program Type: Green Schools, Open Space

GI Concepts: Porous Pavement, Green Roof, Bioretention

Field Notes:

- School has large flat parking lot without many grate inlets. Porous pavement could be installed at some of the parking spaces
- Parking lot pavement appear to be in good shape and installation of porous pavement would likely be a stand-alone project
- Ample green space behind football field bleachers to implement bioretention to receive runoff from the east parking lot
- Gymnasium has a flat roof that could be used for green roof installation
- Flat roof with internal roof drain appear to be connected to the sewer system. These could be disconnected to green spaces within the courtyard

Pros:

- Significant stormwater capture potential
- Educational opportunities at the school
- Open space and parking areas typically easier and more cost-effective to implement
- Site is upstream of sewers with significant capacity limitations

Cons:

- Parking lot appears in good shape and any green technology implementation would likely be a stand-alone project.
- Construction possibly limited to summer months (on the school parcel)

Bradlee Shopping Center

South Entrance to Shopping Center[1]

Parking Lot Runoff Exit Location to Street

Median Space avalable for Bioretention

Alley behind West Wing of the Shopping Centre

[1]Source: Google Maps Street View ™

Program Type: Green Parking, Green Alley, Green Roof

GI Concepts: Bioretention, Bioswale, Porous Pavement, Underground Cistern, Green Roof

Field Notes:

- Shopping centre has large parking lot with potential for large stormwater capture
- Flat roof with external roof drains connected to impervious surfaces
- Alley behind west end of the shopping center provides opportunity for green alley implementation
- Potential for underground cisterns below parking lots
- Bioretention and bioswale opportunities in median
- Flat roofs with opportunity for green roof

Pros:

- Large stormwater capture potential
- High visibility
- Site is upstream of sewers with significant capacity limitations

Cons:

- Private property

Townhouses at Kenwood Ave

Median Bioretention at Access Drive

Porous Pavement Parking Areas

Program Type: Green Parking

GI Concepts: Porous Pavement Parking, Bioretention/Planters, Blue Street

Field Notes:

- Large asphalt parking lot and access drives with gentle slope provide opportunity for blue street and porous pavement
- Raised curbs and inlets available for implementation of bioretention/planters
- Disconnected roof drains to small patches of grass show erosion spots

Pros:

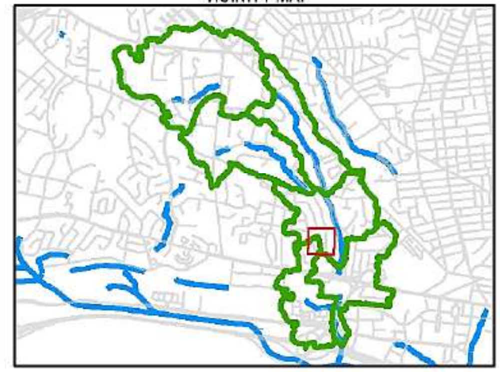
- Large stormwater capture potential
- Median stormwater capture and soil amendment
- Parking areas typically easier and more cost-effective to implement

Cons:

- Multiple private ownership

Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	12,466	149,594	93,247
Porous Pavement	35,540	71,081	44,307
Total	**48,006**	**220,674**	**137,554**

VICINITY MAP



LEGEND
- Contours (ft)
- Parcels
- Watershed
- City of Alexandria Streams

Green Infrastructure Concepts
- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)

N

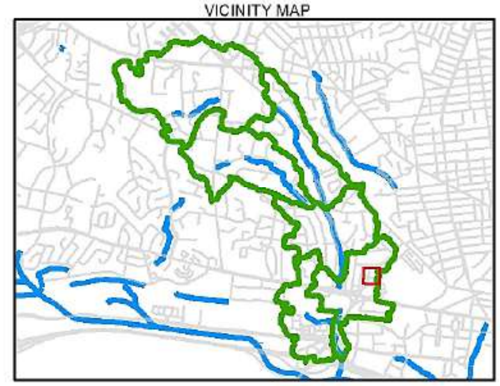
0 50 100 200
Feet

Sky Hill Road

Bioretention/Planters, Porous Pavement
Task 4 - Identify Problems and Develop Solutions
City of Alexandria Storm Sewer Capacity Analysis

Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	10,099	121,190	75,542
Porous Pavement	2,037	4,074	2,540
Total	**12,136**	**125,264**	**78,081**

VICINITY MAP



LEGEND

Contours (ft)

Parcels

Watershed

City of Alexandria Streams

Green Infrastructure Concepts

Bioretention/Planters

Cisterns

Green/Blue Roofs

Porous Pavement

Stream Daylighting

Surface Storage (Blue Streets)

N

0 25 50 100

Feet

Roberts Lane

Bioretention/Planters, Porous Pavement

Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

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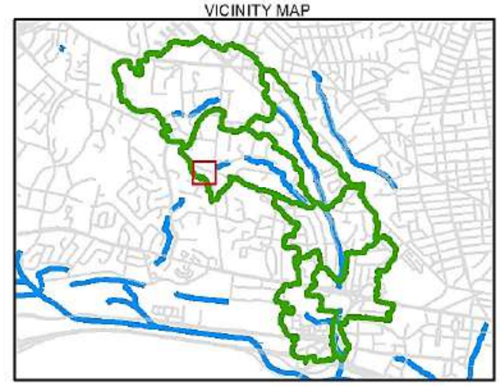
Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	26,100	313,205	195,231

VICINITY MAP



LEGEND
- Contours (ft)
- Parcels
- Watershed
- City of Alexandria Streams

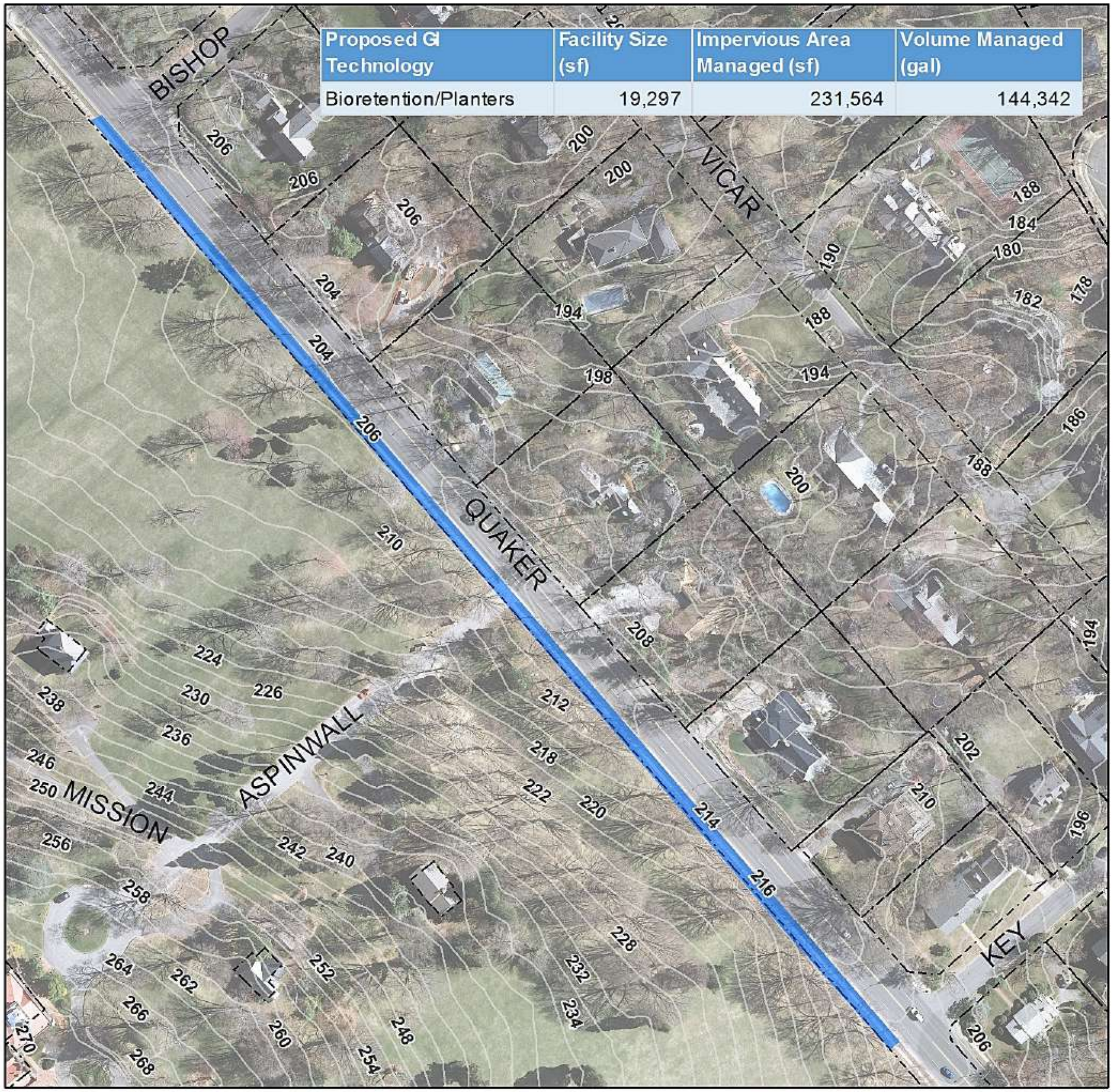
Green Infrastructure Concepts
- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)

N

0 50 100 200
Feet

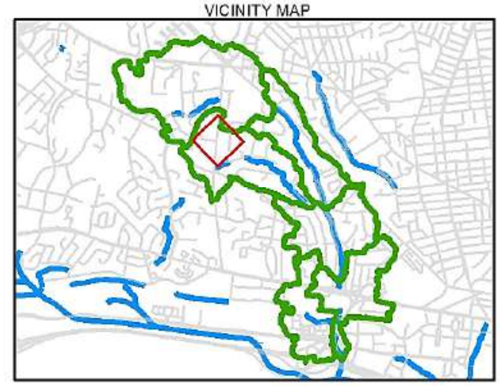
Seminary Road
Bioretention/Planters
Task 4 - Identify Problems and Develop Solutions
City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL



Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	19,297	231,564	144,342

VICINITY MAP



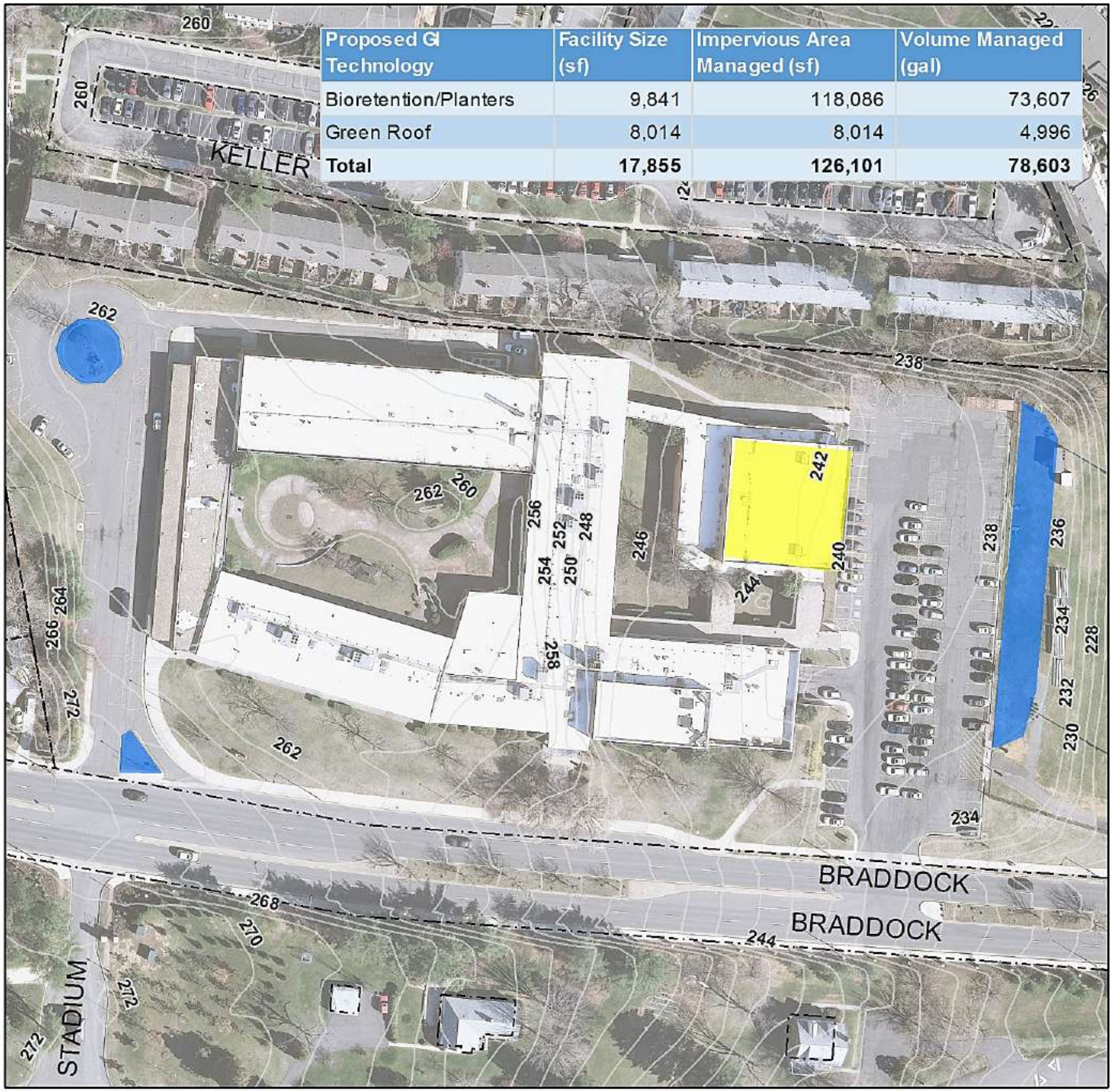
LEGEND
Contours (ft)
Parcels
Watershed
City of Alexandria Streams

Green Infrastructure Concepts
Bioretention/Planters
Cisterns
Green/Blue Roofs
Porous Pavement
Stream Daylighting
Surface Storage (Blue Streets)

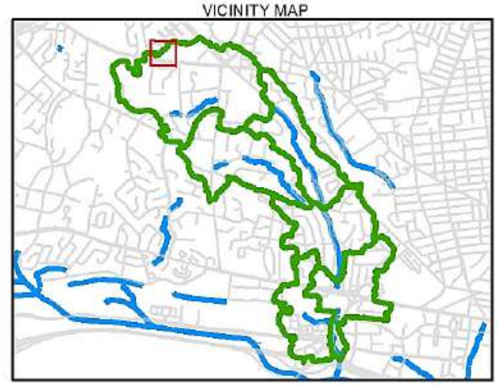
0 50 100 200
Feet

North Quaker Lane
Bioretention/Planters
Task 4 - Identify Problems and Develop Solutions
City of Alexandria Storm Sewer Capacity Analysis

Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	9,841	118,086	73,607
Green Roof	8,014	8,014	4,996
Total	**17,855**	**126,101**	**78,603**



VICINITY MAP



LEGEND

Contours (ft)

Parcels

Watershed

City of Alexandria Streams

Green Infrastructure Concepts

Bioretention/Planters

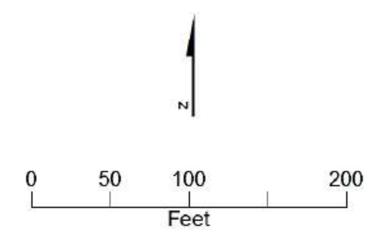
Cisterns

Green/Blue Roofs

Porous Pavement

Stream Daylighting

Surface Storage (Blue Streets)



Minnie Howard School

Bioretention/Planters, Green/Blue Roofs

Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

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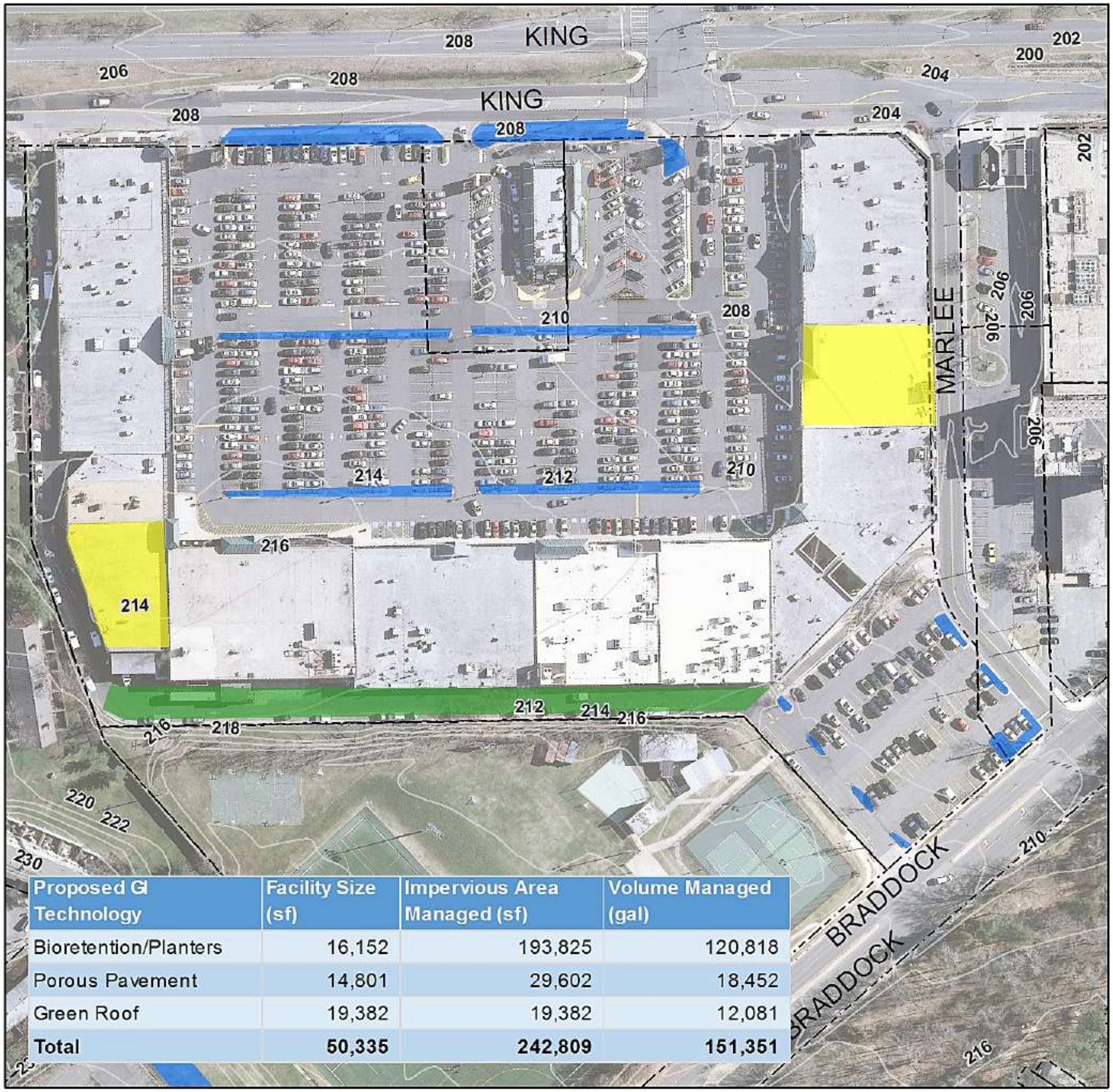
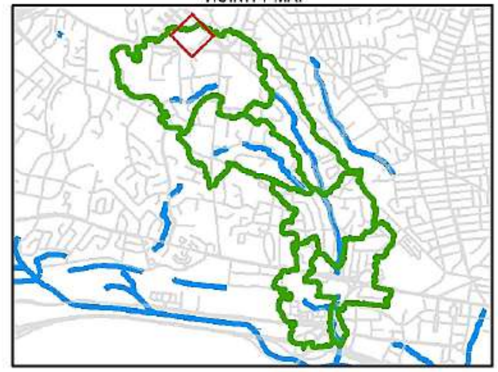


Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	16,152	193,825	120,818
Porous Pavement	14,801	29,602	18,452
Green Roof	19,382	19,382	12,081
Total	**50,335**	**242,809**	**151,351**

VICINITY MAP



LEGEND
- Contours (ft)
- Parcels
- Watershed
- City of Alexandria Streams

Green Infrastructure Concepts
- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)

0 50 100 200
Feet

Bradlee Shopping Center

Bioretention/Planters, Porous Pavement, Green/Blue Roofs

Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

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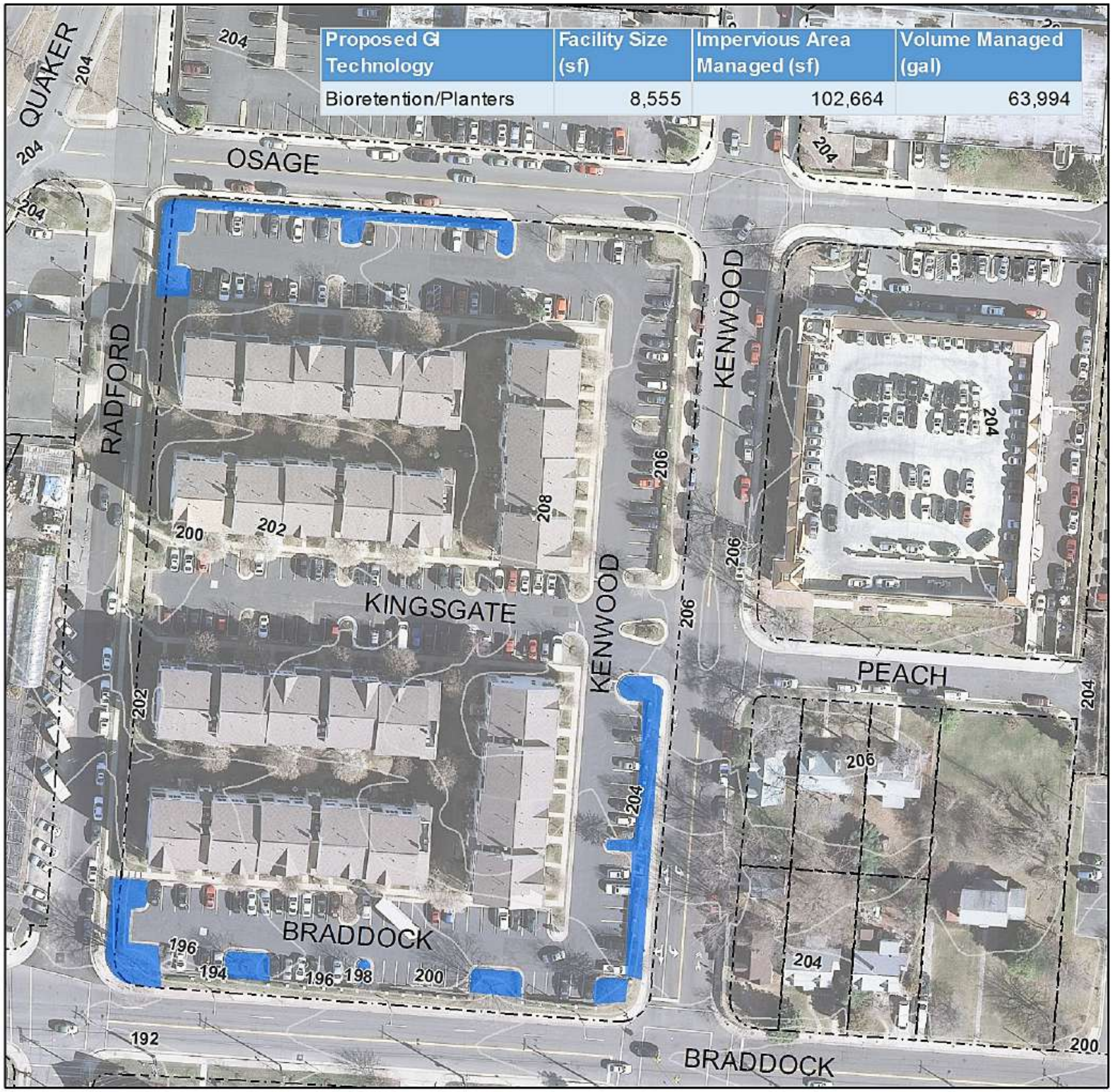
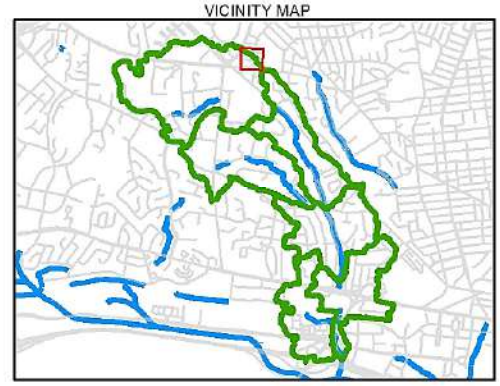
Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal)
Bioretention/Planters	8,555	102,664	63,994



VICINITY MAP



LEGEND
- Contours (ft)
- Parcels
- Watershed
- City of Alexandria Streams

Green Infrastructure Concepts
- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)

N

0 50 100 200
Feet

Kenwood Avenue Townhouses
Bioretention/Planters
Task 4 - Identify Problems and Develop Solutions
City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL

FACT SHEET: BIORETENTION AND STORMWATER PLANTERS

Rain garden in a public park setting in Lancaster, PA

Right-of-way bioretention planting in Syracuse, NY

Bioretention areas (often called Rain Gardens) are shallow surface depressions planted with specially selected native vegetation to treat and capture runoff and are sometimes underlain by sand or a gravel storage/infiltration bed. Bioretention is a method of managing stormwater by pooling water within a planting area and then allowing the water to infiltrate into the garden soils. In addition to managing runoff volume and mitigating peak discharge rates, this process filters suspended solids and related pollutants from stormwater runoff.

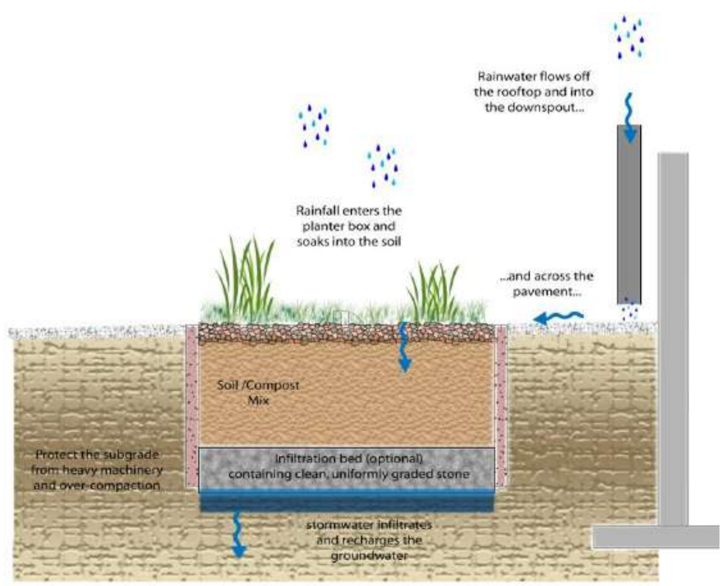
Bioretention can be designed into a landscape as a garden feature that helps to improve water quality while reducing runoff quantity. Rain Gardens can be integrated into a site with a high degree of flexibility and can balance nicely with other structural management systems including porous pavement parking lots, infiltration trenches, and non-structural stormwater BMPs. Bioretention areas typically require little maintenance once fully established and often replace areas that were intensively landscaped and required high maintenance.

A Stormwater Planter is a container or enclosed feature located either above ground or below ground, planted with vegetation that captures stormwater within the structure itself.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile w/ broad applicability
- Enhanced site aesthetics and habitat
- Potential air quality & climate benefits

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes (Planters)
Industrial	Yes
Retrofit	Yes
Recreational	Yes
Public/Private	Yes



Conceptual cross-section showing planter with infiltration

VARIATIONS

- Subsurface storage/infiltration bed
- Use of underdrain and/or impervious liner
- Planters – Contained (above ground), infiltration (below ground), flow-through
- Pre-treatment incorporated into design

KEY DESIGN FEATURES

- Ponding depths 6 to 18 inches for drawdown within 48 hours
- Plant selection (native vegetation that is tolerant of hydrologic variability, salts, and environmental stress)
- Amended or engineered soil as needed
- Stable inflow/outflow conditions and positive overflow for extreme storm events
- Planters may require flow bypass during winter
- Planters - Captured runoff to drain out in 3 to 4 hours after storm even unless used for irrigation

SITE FACTORS

- Water Table/ Bedrock Separation: 2-foot minimum, 4-foot recommended (N/A for contained planter)
- Soils: HSG A and B preferred; C & D may require an underdrain (N/A for contained planter)
- Feasibility on steeper slopes: medium
- Potential Hotspots: yes with pretreatment and/or impervious liner, yes for contained planter
- Maximum recommended drainage area loading: 15:1; not more than 1 acre to one rain garden

MAINTENANCE

- Often requires watering during establishment
- Spot weeding, pruning, erosion repair, trash removal, mulch reapplication (as needed) required 2-3x/growing season
- Maintenance tasks and costs are similar to traditional landscaping

COST

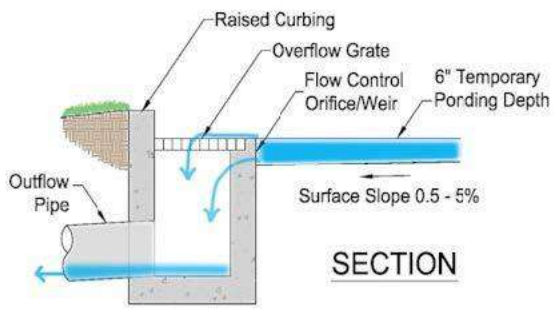
- Bioretention costs will vary depending on size/vegetation type/storage elements; typical costs $10-25/ sq. ft.

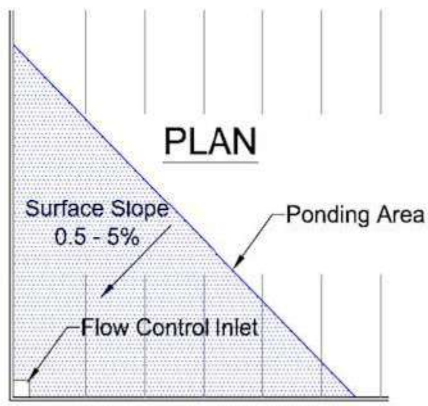
POTENTIAL LIMITATIONS

- Higher maintenance until vegetation is established
- Limited impervious drainage area to each BMP
- Requires careful selection & establishment of plants

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Low/Medium
Peak Rate	Medium	TN	Medium	Winter Performance	Medium
Erosion Reduction	Medium	Temperature	Medium/High	Fast Track Potential	Medium
Flood Protection	Medium			Aesthetics	High

FACT SHEET: BLUE STREETS





Blue streets refer to the practice of temporarily detaining stormwater, delaying its release and reducing its peak flow rate into the storm sewer system.

Surface storage practices have been used traditionally on rooftops (i.e. blue roofs) and in parking lots but can also be implemented in residential streets and right-of-ways with lower traffic volumes. These "blue streets" can be a cost-effective way to manage stormwater and address surcharging without significant subsurface excavation and construction interventions.

Surface storage is typically accomplished using drainage structures and retrofitting existing catch basins to feature devices such as orifice restrictors or vortex restrictors. Blue streets also emphasize minimizing the number of catch basins to the extent practical.

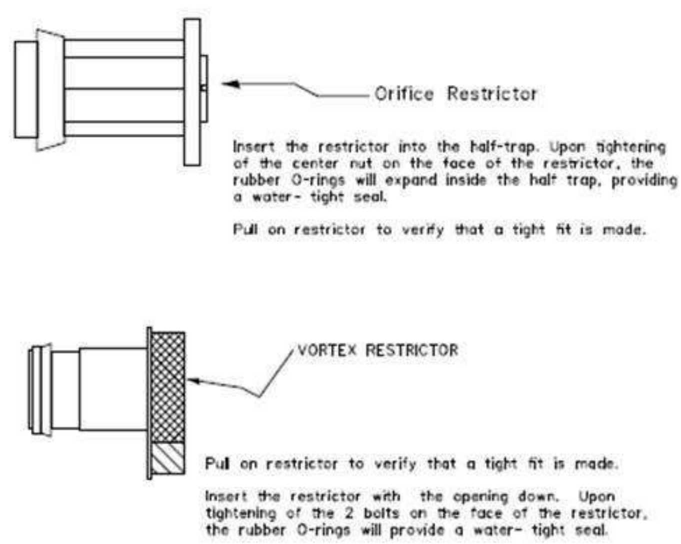
Blue streets (surface storage techniques) are often best implemented in alleys, low volume roads, and on private sites, for public perception and safety reasons.

BENEFITS

- Reduces stress on drainage system
- Mitigates peak rate flow
- Cost-effective technique to manage stormwater
- Short duration storage
- Reduces need for subsurface excavation and construction

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Limited for Highway
Recreational	Yes
Public/Private	Yes/Yes

DRAINAGE STRUCTURES RESTRICTORS



Drainage structure restrictors are key features of surface storage and blue streets. Source: City of Chicago design manual

VARIATIONS

- Flow control structures
- Orifice restrictors
- Vortex restrictors
- Reduction in number of catch basins/inlets on a street

KEY DESIGN FEATURES

- Emergency overflows typically required
- Maximum ponding depths (less than one foot)
- Adequate surface slope to outlet
- Traffic volume, public safety, and user inconvenience must be taken into account

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – N/A
- Slope – Requires relatively low slopes to provide appreciable storage
- Potential hotspots – yes
- Maximum drainage area – relatively small DA to individual inlets (similar to conventional inlets)

MAINTENANCE

- Clean drainage structures and repair/replace parts as needed

COST

- Drainage structures restrictors range in cost, for example installing a vortex restrictor can be approximately $1000 per inlet

POTENTIAL LIMITATIONS

- Not suitable for heavily-used roadways without adequate median/shoulder space
- Excess ponding on roadways may freeze in winter conditions
- Public safety perceptions and concerns
- Does not inherently address water quality and quantity – should generally be combined with other BMPs

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low	TSS	Low	Capital Cost	Low
Groundwater Recharge	Low	TP	Low	Maintenance	Low/Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	High
Flood Protection	Medium			Aesthetics	Low

FACT SHEET: CISTERNS/RAIN BARRELS

Example of above-ground cistern with vegetation screening

Cisterns (or rain barrels) are structures designed to intercept and store runoff from rooftops to allow for its reuse, reducing volume and overall water quality impairment. Stormwater is contained in the cistern structure and typically reused for irrigation or other water needs. This GI technology reduces potable water needs while also reducing stormwater discharges.

Cisterns can be located above or below ground and are containers or tanks with a larger storage capacity than a rain barrel, and often used to supplement grey water needs (i.e. toilet flushing) in a building, as well as irrigation. Rain barrels are above-ground structures connected to rooftop downspouts that collect rainwater and store it until needed for a specific use, such as landscape irrigation.

Cisterns and rain barrels can be used in suburban and urban areas where the need for supplemental onsite irrigation or other high water uses is especially apparent.

BENEFITS

- Provides supplemental water supply
- Wide applicability
- Reduces potable water use
- Related cost savings and environmental benefits
- Reduces stormwater runoff impacts

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes, if demand exists
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes

Rain barrel prototype example

VARIATIONS

- Cisterns – can be either underground and above ground
- Water storage tanks
- Storage beneath a usable surface using manufactured stormwater products (chambers, pipes, crates, etc.)
- Various sizes, materials, shapes, etc.

KEY DESIGN FEATURES

- Small storm events are captured with most structures
- Provide overflow for large storms events
- Discharge/use water before next storm event
- Consider site topography, placing structure upgradient of plantings (if applicable) in order to eliminate pumping needs

SITE FACTORS

- Water table to bedrock depth – N/A (although must be considered for subsurface systems)
- Soils – N/A
- Slope – N/A
- Potential hotspots – typically N/A for rooftop runoff
- Maximum drainage area – typically relatively small, based on storage capacity

MAINTENANCE

- Use stored water and/or discharge before next storm event
- Clean annually and check for loose valves, leaks, etc. monthly during active season
- May require flow bypass valves or be taken offline during the winter

COST

- Cisterns typically cost from $3 to $8/gallon/ Rain Barrels range from $75 to $300 each

POTENTIAL LIMITATIONS

- Manages only relatively small storm events which requires additional management and use for the stored water.
- Typically requires additional management of runoff
- Requires a use for the stored water (irrigation, gray water, etc.)

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low/Medium	TSS	Medium	Capital Cost	Medium
Groundwater Recharge*	Low/Medium	TP	Medium	Maintenance	Medium
Peak Rate*	Low	TN	Low	Winter Performance	Low
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	Medium/High
Flood Protection*	Low			Aesthetics	Low/Medium

**Although stand-alone cisterns are expected to have lower benefits in these categories, if combined with downspout disconnection to landscaped areas the benefits can be increased significantly.*

FACT SHEET: VEGETATED (GREEN) ROOFS AND BLUE ROOFS

Green roof (Philadelphia, PA)

Blue roof (NYC) / Photo – Gowanus Canal Conservancy

BENEFITS

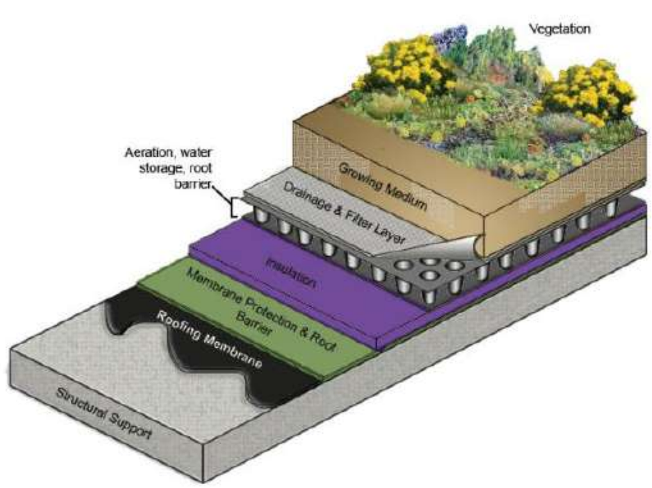
- High volume reduction (annual basis)
- Moderate ecological value and habitat (green roofs)
- High aesthetic value (green roofs)
- Energy benefits (heating/cooling)
- Urban heat island reduction

POTENTIAL APPLICATIONS	
Residential	Limited
Commercial	Yes
Ultra-Urban	Yes
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes

A green roof is a veneer of vegetation that is grown on and covers an otherwise conventional flat or pitched roof, endowing the roof with hydrologic characteristics that more closely match surface vegetation. The overall thickness of the veneer typically ranges from 2 to 6 inches and may contain multiple layers, such as waterproofing, synthetic insulation, non-soil engineered growth media, fabrics, and synthetic components. Vegetated roofs can be optimized to achieve water quantity and water quality benefits. Through the appropriate selection of materials, even thin vegetated covers can provide significant rainfall retention and detention functions.

Depending on the plant material and planned usage for the roof area, modern vegetated roofs can be categorized as systems that are intensive (usually > 6 inches of substrate), semi-intensive, or extensive (<4 inches). More maintenance, higher costs and more weight are the characteristics for the intensive system compared to that of the extensive vegetated roof.

Another GI rooftop technology - **Blue roofs -** are non-vegetated systems that employ stormwater control devices to temporarily store water on the rooftop and then release it into the drainage system at a relatively low flow rate. Storage can be provided by modifying roof drains or through the use of detention trays that sometimes have a lightweight gravel media. Blue roof and green roof technologies can also be combined in a design to achieve



Cross-section showing components of vegetated roof system

VARIATIONS

- Green roofs - single media system, dual media system (with synthetic liner)
- Green roofs - Intensive, Extensive, or Semi-intensive

KEY DESIGN FEATURES

- Engineered media should have a high mineral content and is typically 85% to 97% nonorganic.
- 2-6 inches of non-soil engineered media; assemblies that are 4 inches and deeper may include more than one type of engineered media.
- Irrigation is generally not required (or even desirable) for optimal stormwater management
- Internal building drainage, including provision to cover and protect deck drains or scuppers, must anticipate the need to manage large rainfall events without inundating the vegetated roof system.
- Assemblies planned for roofs with pitches steeper than 2:12 (9.5 degrees) must incorporate supplemental measures to insure stability against siding.
- The roof structure must be evaluated for compatibility with the maximum predicted dead and live loads. Typical dead loads for wet extensive vegetated covers range from about 12 to 36 pounds per square foot.
- Waterproofing must be resistant to biological and root attack. In many instances a supplemental root barrier-layer is installed to protect the primary waterproofing.
- Blue roofs: roof structure, waterproofing, accommodation for larger storm events/emergency overflows

MAINTENANCE

- Once vegetation is fully established, little maintenance needed for the extensive system
- Maintenance cost is similar to native landscaping, \$0.10-\$0.35 per square foot
- Blue roof maintenance is similar to conventional roof maintenance (cleaning roof and drains as necessary)

COST

- Green roofs: \$10 - \$35 per square foot, including all structural components, soil, and plants; more expensive than traditional roofs, but have longer lifespan; generally less expensive to install on new roof versus retrofit on existing roof
- Blue roofs: Typically add only \$1-\$5 per square foot compared to traditional roofs

POTENTIAL LIMITATIONS

- Green roofs have higher maintenance needs until vegetation is established
- Need for adequate roof structure and waterproofing; can be challenging on retrofit application

STORMWATER QUANTITY FUNCTIONS*		STORMWATER QUALITY FUNCTIONS*		ADDITIONAL CONSIDERATIONS	
Volume	Medium/High	TSS	Low/Medium	Capital Cost	High
Groundwater Recharge	Low	TP	Low/Medium	Maintenance	Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low/Medium	Temperature	Medium	Fast Track Potential	Low
Flood Protection	Low/Medium			Aesthetics	High

**For green roofs, blue roofs primarily function for peak rate control and flood protection.*

FACT SHEET: POROUS PAVEMENT

Porous asphalt basketball courts (Lancaster, PA)

Porous (pervious) pavement is a Green Infrastructure (GI) technique that combines stormwater infiltration, storage, and a structural pavement consisting of a permeable surface underlain by a storage/infiltration bed. Porous pavement is well suited for parking areas, walking paths, sidewalks, playgrounds, plazas, basketball courts, and other similar uses.

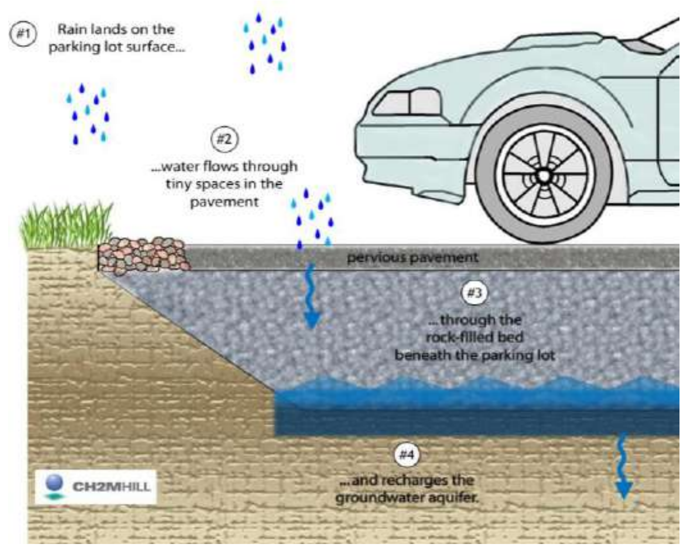
A porous pavement system consists of a pervious surface course underlain by a storage bed, typically placed on uncompacted subgrade to facilitate stormwater infiltration. The subsurface storage reservoir may consist of a stone bed of uniformly graded, clean and washed course aggregate with a void space of approximately 40% or other manufactured structural storage units. Porous pavement may be asphalt, concrete, permeable paver blocks, reinforced turf/gravel, or other emerging types of pavement.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile with broad applicability
- Dual use for pavement structure and stormwater management
- Pavers come in range of sizes and colors
- Opportunity for public education/demonstration

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra Urban	Yes
Industrial	Limited
Retrofit	Yes
Highway	Limited
Recreational	Yes
Public/Private	Yes/Yes

Porous pavers (San Diego)



Conceptual diagram showing how porous pavement functions

KEY DESIGN FEATURES

- Soil testing required for infiltration designs
- Limit amount of adjacent areas that drain directly onto the surface of the porous pavement
- Uncompacted soil subgrade for infiltration
- Level storage bed bottoms
- Provide positive storm water overflow from bed
- Surface permeability greater than 20 inches per hour
- Secondary inflow mechanism recommended
- Pretreatment for sediment-laden runoff, limit sources of sediment/debris deposition

SITE FACTORS

- Water Table/Bedrock Separation: 2-foot minimum
- Soils: HSG A&B preferred; HSG C&D may require underdrains
- Feasibility on steeper slopes: Low
- Potential Hotspots: Not without design of pretreatment system/impervious liner

MAINTENANCE

- Clean inlets
- Vacuum biannually
- Maintain adjacent landscaping/planting beds
- Periodic replacement of aggregate in paver block joints (if applicable)
- Careful winter maintenance (no sand or other abrasives, careful plowing)

COST

- Varies by porous pavement type
- Local quarry needed for stone filled infiltration bed
- Typically $7-$15 per square foot, including underground stormwater storage bed
- Generally more than standard pavement, but saves on cost of other BMPs and traditional drainage infrastructure

POTENTIAL LIMITATIONS

- Careful design & construction required
- Pervious pavement not suitable for all uses/not suitable for steep slopes
- Higher maintenance needs than standard pavement

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS*	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Medium
Peak Rate	Medium/High	TN	Medium	Winter Performance	Medium/High
Erosion Reduction	Medium/High	Temperature	High	Fast Track Potential	Low/Medium
Flood Protection	Medium/High			Aesthetics	Low to High

** While porous pavements typically result in low TSS loads, sources of sediment should be minimized to reduce the risk of clogging.*

FACT SHEET: SOIL AMENDMENTS

Healthy soils help vegetation thrive while also increasing soil infiltration rates Photo: S.Coronado

Soil amendments can include a variety of practices that reduce the generation of runoff by improving vegetation growth, increasing water infiltration, and improving water holding capacity. For example, on existing turf grass, soil amendments can include placing a thin layer of compost or other materials and spreading them evenly over existing vegetation. Amendments on existing turf grass areas can be applied for several years to improve soil over time. Soil testing can indicate how many applications are appropriate. Existing grass areas can also be aerated to improve water transmission and allow for deeper incorporation of compost.

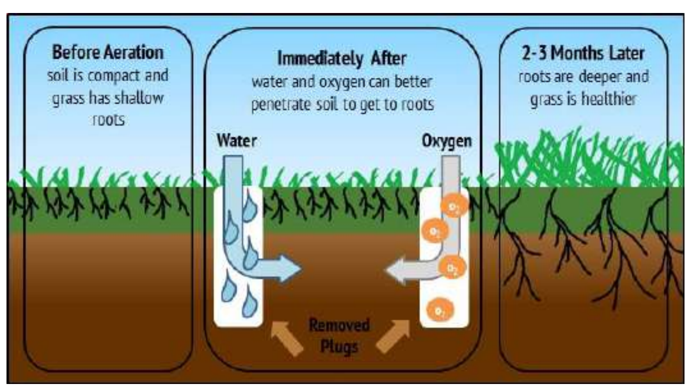
On new construction, redevelopment, and restoration projects, compost can be applied and deeply tilled into compacted soils to restore their porosity before the areas are re-vegetated (potentially with native landscaping, combining the benefits of both GI strategies).

BENEFITS

- Enhanced soil health and vegetation growth/root depth
- Improved soil infiltration rates
- Enhanced soil water holding capacity
- Reduced stormwater runoff from soil surface

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Yes
Recreational	Yes
Public/Private	Yes/Yes

A variety of soil amendments are available depending on the specific soil conditions and desired result. Photo: Pahls Market



Physical aeration (tilling) can also help improve soil health and soil permeability/porosity. Image: GreenMaxLawns

VARIATIONS

- Treating turf grass or areas with more intensive plant palettes
- Combining amended soil areas with downspout disconnection
- Physical aeration/tilling of turf grass/vegetated areas can help to remedy soil compaction
- Compost, sand, microbes, mycorrhizae, gypsum, biochar, manure, worm castings, etc.
- Amendments can improve soil aggregation, increase porosity, and improve aeration and rooting depth

KEY DESIGN FEATURES

- Soil bulk density and soil nutrient testing required
- Existing soil conditions should be evaluated before forming an amendment strategy

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – Bulk density and nutrient levels
- Slope – Not recommended for use on slopes greater than 3:1
- Potential hotspots – N/A
- Maximum drainage area – N/A

MAINTENANCE

- Replenishment of amendments on a regular basis may be required
- Aeration of soil often done at same time

COST

- The cost of soil amendments ranges widely depending on the size and type. Larger projects are estimated to cost approximately $5,000 per acre.

POTENTIAL LIMITATIONS

- Viability depends upon soil testing results
- Certain types of soil may not be favorable for success with amendments
- Not a regulated industry – testing of amendment may be needed to ensure specifications
- Physical aeration should not be done near existing tree roots

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Medium	TSS*	Medium	Capital Cost	Low
Groundwater Recharge	Medium	TP*	Medium	Maintenance	Low/Medium
Peak Rate	Medium	TN*	Medium	Winter Performance	Medium
Erosion Reduction	High	Temperature	Low	Fast Track Potential	Medium
Flood Protection	Low/Medium			Aesthetics	Medium

**Water quality benefits expected to vary widely depending on the condition of the soil/landscape prior to soil amendments.*

Appendix D
Alternatives Analysis Results

Appendix D - Alternative Analysis Summary

Tabulation of Solutions, Costs, and Scoring for Taylor Run High-Priority Problem Areas

		Solution Summary			Flood Volume Summary					Weighted Solution Score								
Problem Area ID	Solution Technology (Conveyance, Storage, Low GI, Medium GI, High GI)	Project Name	Cost ($M)	Benefit-Cost Ratio	Existing Flood Volume (MG)	Solution Flood Volume (MG)	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)	Urban Drainage/ Flooding	Environmental Compliance	EcoCity Goals/ Sustainability	Social Benefits	Integrated Asset Management	City-Wide Maintenance Implications	Constructability	Public Acceptance	Total
201	Conveyance	CONV-201	$ 1.803	12.9	1.84	0.68	1.16	63%	$ 1.55	0.0	0.0	0.0	0.0	0.0	16.2	2.2	4.8	23.2
201	Storage	STOR-201	$ 0.297	47.3	1.84	1.66	0.18	10%	$ 1.64	1.7	0.0	0.0	0.0	0.0	3.2	4.3	4.8	14.1
201	Low GI	LGI-201	$ 0.220	230.8	1.84	1.79	0.05	3%	$ 4.35	0.5	1.6	3.9	3.1	13.2	13.0	10.8	4.8	50.8
201	Medium GI	MGI-201	$ 1.223	44.9	1.84	1.69	0.15	8%	$ 8.15	1.4	4.7	3.9	3.1	13.2	13.0	10.8	4.8	54.9
201	High GI	HGI-201	$ 2.218	26.6	1.84	1.58	0.26	14%	$ 8.50	2.4	7.8	3.9	3.1	13.2	13.0	10.8	4.8	59.0
202	Conveyance	CONV-202	$ 0.354	103.6	0.27	0.06	0.21	79%	$ 1.69	13.5	0.0	0.0	0.0	0.0	16.2	2.2	4.8	36.7
202	Low GI	LGI-202	$ 0.025	1494.7	0.27	0.26	0.00	1%	$ 7.69	0.2	1.9	4.5	3.6	6.6	13.0	2.2	4.8	36.7
202	Medium GI	MGI-202	$ 0.136	299.7	0.27	0.26	0.01	4%	$ 13.97	0.6	5.6	4.5	3.6	6.6	13.0	2.2	4.8	40.8
202	High GI	HGI-202	$ 0.247	182.1	0.27	0.25	0.02	6%	$ 14.94	1.1	9.3	4.5	3.6	6.6	13.0	2.2	4.8	45.0
203	Conveyance	CONV-203	$ 0.221	212.2	0.95	-	0.95	100%	$ 0.23	17.1	0.0	0.0	0.0	6.6	16.2	2.2	4.8	46.9
203	Storage	STOR-203	$ 0.196	57.5	0.95	0.89	0.06	6%	$ 3.34	1.1	0.0	0.0	0.0	0.0	3.2	2.2	4.8	11.3
203	Low GI	LGI-203	$ 0.083	319.7	0.95	0.93	0.02	2%	$ 4.37	0.3	1.9	3.6	2.9	0.0	13.0	0.0	4.8	26.5
203	Medium GI	MGI-203	$ 0.460	67.1	0.95	0.90	0.05	5%	$ 8.79	0.9	5.7	3.6	2.9	0.0	13.0	0.0	4.8	30.9
203	High GI	HGI-203	$ 0.835	41.7	0.95	0.89	0.06	7%	$ 12.97	1.2	9.4	3.6	2.9	0.0	13.0	0.0	4.8	34.9
204	Conveyance	CONV-204	$ 0.373	113.9	0.08	-	0.08	100%	$ 4.43	17.1	0.0	0.0	0.0	0.0	16.2	4.3	4.8	42.5
204	Low GI	LGI-204	$ 0.052	707.9	0.08	0.08	0.00	1%	$ 42.76	0.2	1.6	3.6	2.9	6.6	13.0	4.3	4.8	37.0
204	Medium GI	MGI-204	$ 0.290	140.1	0.08	0.08	0.00	5%	$ 75.53	0.8	4.7	3.6	2.9	6.6	13.0	4.3	4.8	40.7
204	High GI	HGI-204	$ 0.527	84.2	0.08	0.08	0.01	8%	$ 80.67	1.3	7.8	3.6	2.9	6.6	13.0	4.3	4.8	44.3
205	Conveyance	CONV-205	$ 0.390	107.1	1.37	0.41	0.96	70%	$ 0.41	5.4	0.0	0.0	0.0	13.2	16.2	2.2	4.8	41.8
205	Storage	STOR-205	$ 1.907	9.8	1.37	0.86	0.51	37%	$ 3.74	6.4	0.0	0.0	0.0	0.0	3.2	4.3	4.8	18.7
205	Low GI	LGI-205	$ 0.048	770.1	1.37	1.35	0.02	1%	$ 2.62	0.2	1.3	3.6	2.9	6.6	13.0	4.3	4.8	36.8
205	Medium GI	MGI-205	$ 0.265	150.2	1.37	1.32	0.05	4%	$ 4.90	0.7	3.9	3.6	2.9	6.6	13.0	4.3	4.8	39.8
205	High GI	HGI-205	$ 0.481	89.1	1.37	1.28	0.09	6%	$ 5.43	1.1	6.5	3.6	2.9	6.6	13.0	4.3	4.8	42.8
206	Conveyance	CONV-206	$ 0.238	218.4	0.10	-	0.10	100%	$ 2.33	17.1	0.0	0.0	2.9	6.6	16.2	4.3	4.8	52.0
206	Storage	STOR-206	$ 0.375	68.1	0.10	0.03	0.07	73%	$ 5.06	12.4	0.0	0.0	2.9	0.0	3.2	2.2	4.8	25.5
206	Low GI	LGI-206	$ 0.042	708.9	0.10	0.10	0.00	2%	$ 20.03	0.3	2.5	4.2	4.8	0.0	13.0	0.0	4.8	29.6
206	Medium GI	MGI-206	$ 0.232	152.0	0.10	0.10	0.01	6%	$ 39.26	1.0	7.5	4.2	4.8	0.0	13.0	0.0	4.8	35.3
206	High GI	HGI-206	$ 0.421	97.1	0.10	0.09	0.01	9%	$ 43.45	1.6	12.5	4.2	4.8	0.0	13.0	0.0	4.8	40.9
207	Conveyance	CONV-207	$ 0.336	126.5	0.41	-	0.41	100%	$ 0.82	17.1	0.0	0.0	0.0	0.0	16.2	4.3	4.8	42.5
207	Low GI	LGI-207	$ 0.065	395.0	0.41	0.41	0.00	1%	$ 20.18	0.1	1.4	3.6	2.9	0.0	13.0	0.0	4.8	25.8
207	Medium GI	MGI-207	$ 0.363	79.7	0.41	0.40	0.01	2%	$ 38.20	0.4	4.3	3.6	2.9	0.0	13.0	0.0	4.8	28.9
207	High GI	HGI-207	$ 0.659	48.6	0.41	0.39	0.02	4%	$ 42.05	0.7	7.1	3.6	2.9	0.0	13.0	0.0	4.8	32.0
208	Conveyance	CONV-208	$ 0.299	134.9	0.12	-	0.12	100%	$ 2.46	17.1	0.0	0.0	0.0	0.0	16.2	2.2	4.8	40.3
208	Storage	STOR-208	$ 0.429	56.1	0.12	0.02	0.10	81%	$ 4.37	13.9	0.0	0.0	0.0	0.0	3.2	2.2	4.8	24.1
208	Low GI	LGI-208	$ 0.041	757.5	0.12	0.12	0.00	2%	$ 22.37	0.3	1.8	1.5	1.2	6.6	13.0	2.2	4.8	31.4
208	Medium GI	MGI-208	$ 0.230	154.2	0.12	0.12	0.01	4%	$ 43.34	0.7	5.4	1.5	1.2	6.6	13.0	2.2	4.8	35.4
208	High GI	HGI-208	$ 0.417	94.7	0.12	0.11	0.01	7%	$ 48.07	1.2	9.0	1.5	1.2	6.6	13.0	2.2	4.8	39.5
209	Conveyance	CONV-209	$ 0.563	95.1	0.23	-	0.23	100%	$ 2.42	17.1	0.0	0.0	0.0	13.2	16.2	2.2	4.8	53.5
209	Storage	STOR-209	$ 0.072	184.9	0.23	0.22	0.01	5%	$ 6.15	0.9	0.0	0.0	0.0	0.0	3.2	4.3	4.8	13.2
209	Low GI	LGI-209	$ 0.251	159.9	0.23	0.23	0.01	3%	$ 43.08	0.4	1.3	5.4	4.3	6.6	13.0	4.3	4.8	40.2
209	Medium GI	MGI-209	$ 1.394	31.3	0.23	0.22	0.02	7%	$ 84.30	1.2	3.9	5.4	4.3	6.6	13.0	4.3	4.8	43.6
209	High GI	HGI-209	$ 2.528	18.6	0.23	0.20	0.03	12%	$ 90.91	2.1	6.6	5.4	4.3	6.6	13.0	4.3	4.8	47.0
210	Conveyance	CONV-210	$ 0.101	401.0	0.01	-	0.01	100%	$ 9.85	17.1	0.0	0.0	0.0	0.0	16.2	2.2	4.8	40.3
210	Storage	STOR-210	$ 0.088	336.6	0.01	0.00	0.01	100%	$ 8.59	17.1	0.0	0.0	0.0	0.0	3.2	4.3	4.8	29.5
210	Low GI	LGI-210	$ 0.014	1976.2	0.01	0.01	0.00	5%	$ 24.14	0.9	1.6	3.6	2.9	0.0	13.0	0.0	4.8	26.8
210	Medium GI	MGI-210	$ 0.075	424.8	0.01	0.01	0.00	18%	$ 42.06	3.0	4.7	3.6	2.9	0.0	13.0	0.0	4.8	32.0
210	High GI	HGI-210	$ 0.137	271.1	0.01	0.01	0.00	29%	$ 46.46	4.9	7.8	3.6	2.9	0.0	13.0	0.0	4.8	37.0
211	Conveyance	CONV-211	$ 0.127	438.2	0.13	-	0.13	100%	$ 0.99	17.1	0.0	0.0	0.0	13.2	16.2	4.3	4.8	55.7
211	Low GI	LGI-211	$ 0.058	657.7	0.13	0.12	0.00	2%	$ 18.55	0.4	1.9	3.8	3.1	6.6	13.0	4.3	4.8	37.9
211	Medium GI	MGI-211	$ 0.320	133.1	0.13	0.12	0.01	8%	$ 33.05	1.3	5.7	3.8	3.1	6.6	13.0	4.3	4.8	42.6
211	High GI	HGI-211	$ 0.581	81.6	0.13	0.11	0.02	13%	$ 34.90	2.2	9.5	3.8	3.1	6.6	13.0	4.3	4.8	47.4
212	Conveyance	CONV-212	$ 0.079	508.6	0.06	-	0.06	100%	$ 1.36	17.1	0.0	0.0	0.0	0.0	16.2	2.2	4.8	40.3
212	Storage	STOR-212	$ 0.247	119.4	0.06	-	0.06	100%	$ 4.24	17.1	0.0	0.0	0.0	0.0	3.2	4.3	4.8	29.5
212	Low GI	LGI-212	$ 0.019	1395.0	0.06	0.06	0.00	3%	$ 10.31	0.5	1.8	3.6	2.9	0.0	13.0	0.0	4.8	26.6
212	Medium GI	MGI-212	$ 0.106	295.5	0.06	0.05	0.01	10%	$ 18.77	1.7	5.4	3.6	2.9	0.0	13.0	0.0	4.8	31.3
212	High GI	HGI-212	$ 0.192	187.4	0.06	0.05	0.01	16%	$ 20.09	2.8	8.9	3.6	2.9	0.0	13.0	0.0	4.8	36.0

Appendix E
Basis of Cost

TECHNICAL MEMORANDUM

City of Alexandria Storm Sewer Capacity Analysis

Planning Level Cost Information

PREPARED FOR:	City of Alexandria Transportation and Engineering Services
COPY TO:	File
PREPARED BY:	CH2M HILL
DATE:	May 15, 2014
PROJECT NUMBER:	240027

Introduction

The City of Alexandria, Virginia, has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented in phases by watershed. The watersheds include Hooffs Run, Four Mile Run, Holmes Run, Cameron Run, Taylor Run, Strawberry Run, Potomac River, and Backlick Run.

This technical memorandum provides details on the basis of cost estimates developed for each solution and the watershed wide alternatives. The information includes panning level unit cost for conveyance, storage and green infrastructure solutions.

These cost estimates are considered a Class 4 - Planning Level estimate as defined by the American Association of Cost Engineering (AACE), International Recommended Practice No. 18R-97, and as designated in ASTM E 2516-06. It is considered accurate to +50% to -30% based up to a 15% complete project definition.

Definitions

The following cost terminologies are used within this technical memorandum:

- Construction cost: Installed cost, including materials, labor, and site adjustment factors such as overcoming utility conflicts, dewatering, and pavement restoration.
- ENRCCI Cost Adjustment Factor: Cost adjustment factor of 0.9 to adjust cost to October 2013 dollars for the DC-Baltimore metro area
- Service and Contingency Factor (SCF) A factor of 1.4 is applied for this project to account for engineering and design expenses (20%) and for contingency allowance (20%).
- Capital cost: Construction cost multiplied by a Service and Contingency Factor (SCF) to cover engineering and design and contingency allowance.
- Operating cost: Operation and maintenance were not considered for this project.

Gravity Sewer Relief Costs

Conveyance projects were costed on a per linear foot basis, based on pipe size and depth. The construction cost rates ($/ft) for gravity sewer replacement are listed in Table 1. Cost rates are shown for different road types. The Gravity sewer cost rates include complete installation of sewer pipes, inlets/manholes, and other ancillary structures as well as surface restoration. The costs were established through literature review and updated based on an assessment of bid tabulation data from Kansas City metro area between 2008 and 2012, and a comparison to Fairfax County, VA unit cost schedule, March 2013. All costs were adjusted to Washington DC, 2013 dollars using Engineering News-Record Construction Cost Index (ENRCCI) adjustment factors.

Factors are applied to the construction cost of gravity sewer pipe replacement to reflect the cost associated with crossing under streams and railroads as listed in Table 2.

Costs of routine O&M, inspection and cleaning at periodic intervals during the life of the gravity sewer were assumed to part of City-wide facilities maintenance plan and should take place even though those costs are not specifically included here.

TABLE 1
Open Cut Gravity Sewer Construction Costs

		Sewer Construction Cost ($/LF) (1)					
		Trench depth up to 10 feet		Trench depth 10 to 15 feet		Trench depth 15 to 20 feet	
Pipe Diameter (in)	Material	Residential	Arterial	Residential	Arterial	Residential	Arterial
8	PVC	$90	$104	$113	$130	$140	$162
10	PVC	$113	$131	$140	$163	$176	$204
12	PVC	$122	$140	$152	$175	$190	$218
15	PVC	$131	$153	$163	$192	$204	$239
18	PVC	$140	$162	$175	$203	$218	$253
21	PVC	$162	$189	$203	$237	$253	$295
24	PVC	$185	$212	$230	$265	$288	$330
30	RCP	$257	$297	$320	$372	$401	$464
36	RCP	$306	$356	$383	$445	$478	$555
42	RCP	$360	$414	$450	$518	$563	$647
48	RCP	$410	$473	$512	$590	$640	$738
54	RCP	$459	$531	$574	$664	$717	$830
60	RCP	$509	$585	$635	$732	$795	$914
72	RCP	$815	$936	$1,018	$1,170	$1,273	$1,463

(1) Listed construction costs have been adjusted to October 2013 dollars using ENRCCI for the DC-Baltimore Metro area.

TABLE 2
Gravity Pipe Construction Cost Factors

Type of Crossing	Cost Factor
Stream	3
Railroad	7

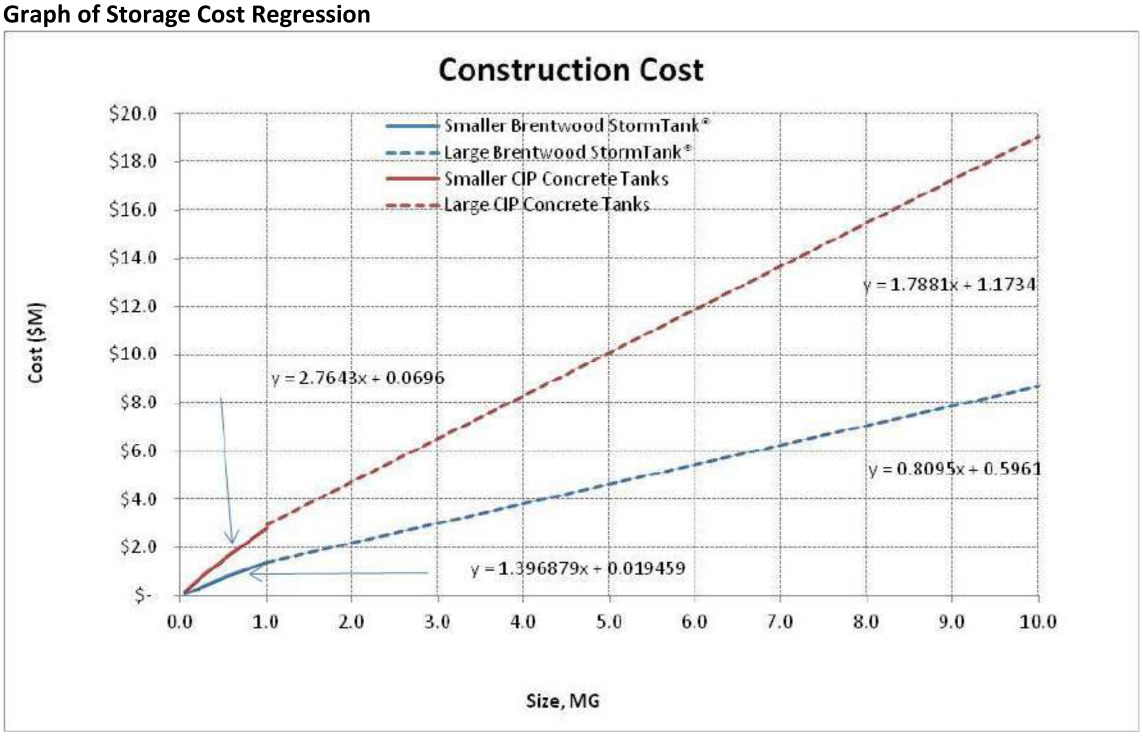
Storage Facility Cost Information

Cost estimates for the storage facilities were developed for two technologies: A traditional underground cast-in-place concrete tank and an alternative stackable modular unit installed underground and wrapped with an impermeable or permeable liner.

The CIP Concrete storage facility construction cost was developed as a customized cost estimate based on CH2M HILL's Program Alternative Cost Calculator (PACC) Tool. The costs are construction costs only and do not include administration costs, engineering costs, contingencies, and other soft costs. The costs for smaller storage units with volumes less than 1 million gallon were found to be high for the CIP concrete tank. Hence, a separate takeoff cost estimate was developed for smaller storage volume; less than 1 million gallons.

A separate cost estimate was developed for the stackable modular units. There is an increasing use of these technologies in the industry and the cost of installation is getting increasingly competitive compared to traditional storage methods. Construction costs were developed based on one such stackable modular unit, StormTank® modules by Brentwood Industries. The cost for the Brentwood StormTank® modules came out significantly less than that for CIP concrete tanks. For the purpose of the evaluation of watershed wide alternative solutions, the StormTank® modules was used as the most cost effective alternative, however site specific conditions will determine which technology will be most appropriate in a given location. For example a site with high water table may make the use of CIP concrete tanks preferable over the StormTank® modules. The estimated construction costs for the CIP concrete tanks and the Brentwood StormTank® are provided in Figure 1.

FIGURE 1
Graph of Storage Cost Regression



The following assumptions were made for storage tank selection and sizing:

1. Offline enclosed underground storage will be active only during wet weather events.
2. Options for odor control were not considered.
3. Costs for storage facilities with intermediate storage volumes were interpolated based on linear regression shown in Figure 1.

Green Infrastructure (GI) Cost Information

A variety of sources and professional judgment were used to develop the GI costs. Where technologies were directly comparable, costs were updated based on Fairfax County, VA unit cost schedule, March 2013. The unit costs used to develop GI implementation cost are included in Table 4. Costs reflecting stand-alone projects (e.g., installing a green roof on top of an existing building) were used for costing alternatives solutions. Incremental costs of adding GI to an existing project can provide significant savings and are provided for reference, but not used directly in cost estimates for this project.

In the CASSCA Project GI is being proposed as a series of GI programs applicable to specific land uses (e.g. green parking is applicable to parking lots). Each GI program may consist of multiple GI technologies which drive the cost of implementing that program. Table 5 lists and the relative amounts of area designated for the GI technologies assumed to be part of each GI program and the resultant unit cost for each GI program.

TABLE 4
Unit Construction Costs of Green Infrastructure Technologies

Green Technology	Stand Alone Cost Proposed for GI Plan ($/GI acre)	Loading Ratio (Ratio of Area Managed to Area of GI)	Stand-Alone Cost Proposed for GI Plan ($/acre managed)	Incremental GI Cost Compared to Stand-Alone
Native Landscaping/Soil Amend.	$ 5,000	1	$ 5,000	50%
Rain Barrels[1] and Native Landscaping/Soil Amend.	$ -	N/A	$ 15,000	90%
Cisterns[2]	N/A	N/A	$ 34,000	90%
Blue Street/Inlet control devices	N/A	N/A	$ 22,500	N/A
Rain Gardens	$ 436,000	12	$ 36,000	70%
Stormwater Trees[3]	$ 34,700	0.5	$ 69,000	50%
Bioswale/Bioretention	$ 1,045,000	12	$ 87,000	70%
Porous Pavement/ Infiltration Trench	$ 436,000	4	$ 109,000	70%
Green Roof[4]	$ 501,000	1	$ 501,000	43%

[1] Each rain barrel is assumed to manage 350 ft^2 of rooftop; therefore, 124.5 barrels are required for 1 acre of roof.
[2] Each 1000-gallon cistern is assumed to manage 6,500 ft^2 of impervious area; therefore, 6.7 barrels are required for 1 acre.
[3] Trees are assumed to have an average 10-foot canopy radius (314 ft^2), with 50 percent assumed to be overhanging impervious area.
[4] Incremental cost of green roofs set to 43 percent to match the District's $5/ ft^2 ($217,800/acre) green roof incentive program.

TABLE 5

Green Infrastructure Technology Elements and Unit Construction Cost of Each Green Program

Green Technology	% Area of Program Assigned to Each GI Technology						
	Blue Streets	**Green Alley**	**Green Buildings**	**Green Parking**	**Green Roofs**	**Green Schools**	**Green Schools**
Native Landscaping/Soil Amend.	-	-		-	-	-	-
Rain Barrels[1] and Native Landscaping/Soil Amend.	-	-	30%	-	-	-	-
Cisterns	-	-	10%	-	-	-	-
Blue Street/Inlet control devices	100%					-	-
Rain Gardens	-	-	30%	-	-	-	-
Stormwater Trees	-	-		-	-	-	30%
Bioswale/Bioretention	-	-	30%	50%	-	65%	30%
Porous Pavement/ Infiltration Trench	-	100%		50%	-	30%	40%
Green Roof	-	-	-	-	100%	5%	-
Unit Cost ($/acre managed)	**$22,500**	**$109,000**	**$44,800**	**$98,000**	**$501,000**	**$114,300**	**$90,400**

Three levels of green infrastructure implementation were evaluated for this project:

- High Implementation – Manage 50% of total impervious area in the shed
- Medium Implementation – Manage 30% of total impervious area in the shed
- Low Implementation – Manage 10% of total impervious area in the shed

The unit cost of implementing GI at the various implementation levels is driven by the availability of GI opportunity areas. As the area available to achieve a GI implementation level become scarce, the cost to achieve that level on GI implementation also increases. It was assumed that GI implementation would focus, in succession, from the most to the least cost effective programs and technologies. That is, for each level of GI implementation the most cost effective program and technologies would be implemented first until the available opportunities for those programs are exhausted. If the level of implementation is not achieved with the most cost effective program, the next most cost effective program is considered in that order until the desired level of GI implementation is achieved. Therefore Low Implementation would be more cost effective (lower cost per acre managed). The unit cost for each implementation level was computed separately for each watershed based on the cost information presented above and the distribution of areas available for GI implementation.

Green Opportunities

Opportunities for blue streets, green streets and alleys, green buildings, green parking, green roofs, and green schools were identified by completing a desktop analysis using the City's 2011 basemap data, including:

- Roads (Road_y and Road_lc)
- Buildings (Blds_y)
- Parking lots (Parking_y)
- Zoning (Zoning_y)
- Parcels (Parcels_y)

The approach to identifying potential opportunities for each program is provided below. All opportunities were combined into a single shapefile of polygons with an attribute for area calculated in acres.

Blue Streets

Local or Residential roads with an average slope less than or equal to 1% and a maximum slope less than or equal to 3%. Road slope was estimated using ArcGIS 3D Analyst tools and the Road_lc feature and City of Alexandria DEM as inputs.

Green Streets and Alleys

Green streets and alleys were identified using the Road_lc and Road_y features to identify roads classed as Arterial, Primary Collector, Residential Collector, Local, and Alley with an average slope less than or equal to 5%. Roadways that fall within school parcels were removed from this layer because they are included in the Green Schools program. Road slope was estimated using ArcGIS 3D analyst tools and the Road_lc feature and City of Alexandria DEM as inputs.

Green Buildings

Green buildings opportunities include buildings where disconnection may be possible. Based on a windshield survey of Taylor Run, approximately 50% of residential buildings, not including single family detached homes, may have opportunities for downspout disconnection. To identify these opportunities, buildings with a BUSE of '1-Residential' were selected from the Blds_y features to identify all residential buildings. This selection was narrowed to apartment buildings and larger residential developments, removing detached houses (BTYPE = 'Detached house'), buildings with less than 5 units (BUNITS < 5), as well as removing nursing homes, hotels, and detention centers. Residential buildings on school properties were also removed because those are accounted for in the Green Schools program. Buildings with a footprint greater than 20,000 square feet were also removed because these buildings are likely too large for a disconnection program.

The footprint of the final selection was reduced by approximately 50% (based on the result of the Taylor Run windshield survey) to approximate the total area of impervious surfaces that could potentially be managed through a disconnection program.

Green Parking

Green parking opportunities were identified as parking lots in the Parking_y feature class with a parking area over 3,000 square feet. Parking lots on school parcels were removed from this selection because they are accounted for in the Green Schools program.

Green Roofs

Green roof opportunities were identified by selecting buildings in the Blds_y feature class with a footprint over 20,000 ft^2 that have a building use (BUSE) of Commercial, Industrial, Institution, Transportation, and Multiple or Mixed use. Also included were buildings over 20,0000 ft^2 that were within a Commercial, Industrial, Coordinated Development District, or Mixed Use zone based on the Zoning_y feature class, unless those buildings were garage/sheds. Buildings on school parcels were removed from this selection because they are accounted for in the Green Schools program.

Green Schools

School parcels were identified by selecting all parcels with a land description (LANDDESC) of 'ED. PUBLIC SCHOOLS', 'PRIVATE ED ENSTS.', or 'ST. ED. INSTITUTIONS' or with an owner name or address that indicated it was school property. School buildings with potential for green roofs were identified by selecting all buildings on school parcels or buildings in the Blds_y features with the word 'school' in the building name (BNAME) or building campus (BCAMPUS) fields where the footprint is over 3,000 ft^2. All remaining impervious surfaces on the school parcels (roads, sidewalks, small buildings, recreation facilities, etc.) were identified as opportunities for green schools.